TAMPEREEN TEKNILLINEN YLIOPISTO
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DELIVERY RELIABILITY IMPROVEMENT PROJECT IN SMALL SERIES PRODUCTION

Master of Science Thesis

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ABSTRACT

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Delivery reliability is an important source of competitive advantage or even a necessity for manufacturing companies. Customer expectations of reliability are increasing. This thesis focuses on small series production, which is characterized by low-volumes of highly customized products. These features bring more variation to the production process. The resulting complexity poses a challenge for production planning and control and makes maintaining a high delivery reliability more difficult. Further, production planning and control is deeply interconnected with other tasks and can easily lead to unintended consequences. Thus, improving delivery reliability is neither straightforward nor simple.

The motivation for this study arose while working on a delivery reliability improvement project in a company. The company produces complex, customized products in small series. The aim of the project was finding root causes of issues in delivery reliability and suggesting improvement measures. The initial approach taken in the project was based on statistical analysis, and it proved unsuited for the case. This generated the need for a new method. The objective of this thesis is therefore to present an effective way to analyze the current state of delivery reliability in a company and to identify measures for improving the situation.

The work was carried out as a case study using the constructive research approach. In order to achieve the objective, a method for carrying out a current state analysis and providing suggestions for improvement was constructed. Knowledge from literature about delivery reliability and from interviews was combined into a cause and effect chart. Ideas from systems thinking were utilized for analyzing the chart by searching for vicious cycles in it. Suggestions for improvement were then based on breaking those cycles. The intention of this method is that the suggested measures will generate lasting improvement rather than simply alleviate the symptoms of the underlying problems.

The improvement method was developed and its feasibility tested in the company's case. As a result, root causes affecting delivery reliability were discovered and ways to improve the situation were suggested. Therefore, the developed method could be determined to be well-suited for its purpose. The improvement method does not include characteristics that would restrict it to small series production or even to the manufacturing industry, so it could be implemented in other kinds of environments as well.

TIIVISTELMÄ

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Toimitusvarmuus on tärkeä kilpailukyvyn lähde, ellei jopa vaatimus valmistaville yrityksille. Asiakkaiden odotukset luotettavuudesta ovat kasvussa. Tässä työssä keskitytään piensarjatuotantoon, jonka toimintaan kuuluvat pieninä määrinä valmistettavat, asiakasräätälöidyt tuotteet. Nämä ominaisuudet tuovat tuotantoprosessiin lisää vaihtelua. Seurauksena on monimutkaisuutta, joka aiheuttaa haasteita tuotannonsuunnittelulle ja -ohjaukselle ja vaikeuttaa korkean toimitusvarmuuden ylläpitämisestä. Tuotannonsuunnittelu ja -ohjaus on lisäksi tiukasti yhteydessä muihin tehtäviin ja se aiheuttaa siten helposti odottamattomia seurauksia. Toimitusvarmuuden parantaminen ei siksi ole suoraviivaista eikä yksinkertaista.

Motivaatio tälle työlle syntyi työskenneltäessä erään yrityksen toimitusvarmuuden parantamisprojektin parissa. Kyseinen yritys valmistaa monimutkaisia, asiakasräätälöityjä tuotteita pienissä sarjoissa. Projektin tavoitteena oli löytää juurisyyt ongelmille toimitusvarmuudessa ja ehdottaa parannuskeinoja. Ensin käytetty lähestymistapa perustui tilastollisen analyysin tekemiseen, ja se osoittautui sopimattomaksi tapaukseen. Tämä loi tarpeen uudelle menetelmälle. Tämän työn tavoitteena on siis esitellä tehokas tapa analysoida yrityksen toimitusvarmuuden nykytilaa ja tunnistaa keinoja tilanteen parantamiseksi.

Työ toteutettiin tapaustutkimuksena käyttäen konstruktiivista tutkimusotetta. Tavoitteen saavuttamiseksi kehitettiin menetelmä nykytila-analyysin toteuttamiseksi ja parannusehdotusten tuottamiseksi. Toimitusvarmuutta käsittelevästä kirjallisuuskatsauksesta ja haastatteluista kerättyä tietoa yhdistettiin syy-seurauskaavioon. Kaavion analysoinnissa hyödynnettiin systeemiajattelua etsimällä kaaviosta noidankehiä. Parannusehdotukset perustuivat kehien purkamiseen. Menetelmän tarkoituksena on ehdottaa keinoja, jotka saavat aikaan kestävää parannusta eivätkä vain helpota perimmäisten ongelmien oireita.

Parannusmenetelmä kehitettiin ja sen käyttökelpoisuutta testattiin ottamalla se käyttöön yrityksen tapauksessa. Tuloksena saatiin selville toimitusvarmuuteen vaikuttavat juurisyyt ja ehdotettiin keinoja tilanteen parantamiseksi. Kehitetty menetelmä voitiin siis todeta toimivaksi. Parannusmenetelmässä ei ole ominaisuuksia, jotka rajoittaisivat sen käytön vain piensarjatuotantoon tai edes valmistavaan teollisuuteen, joten sen voisi ottaa käyttöön myös muunlaisissa ympäristöissä.

PREFACE

This master's thesis is about delivery reliability, a significant feature in any manufacturing company. I'm happy I got to write my thesis on such an important topic. Over the past months I have learned a great deal about factors that affect delivery reliability, but also about other interesting themes, such as systems thinking and conducting research. I have also learned about and hopefully improved my own working habits.

The work on this thesis included a case study in a company. I wish to thank the company for giving me the opportunity of working in a real-life setting. I wish to express my gratitude to the interviewees and everyone else who provided ideas, advice and their time.

This thesis concludes my studies at the Tampere University of Technology. I wish to thank my examiners Tero Juuti and Eeva Järvenpää for their invaluable guidance and encouragement.

Finally, I want to thank my family, friends and especially Sam for their support and unending patience.

Bremen, 19.11.2017

Minna Renko

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LIST OF ABBREVIATIONS

APS	Advanced Planning and Scheduling
ERP	Enterprise Resource Planning
ETO	Engineer To Order
JIT	Just In Time
MES	Manufacturing Execution System
PPC	Production Planning and Control
SCM	Supply Chain Management
SSM	Soft Systems Methodology
TPS	Toyota Production System
WIP	Work In Progress

1. INTRODUCTION

Delivery reliability is the ability to meet delivery dates and quantities. It is an important source of competitive advantage for a company, if not even a vital requirement. (Sarmiento et al. 2007; Nyhuis & Wiendahl 2006.) Expectations on delivery reliability are constantly increasing. Late deliveries can result in high costs whereas punctual deliveries increase customers' trust. (Lödding 2013, p. 1-3.)

There is an increased demand for specialization, calling for low volume, high quality custom products. This thesis focuses on delivery reliability improvement in companies with such small series production. They face very different problems than companies with mass production. They typically deal with a large number of different materials and routing options. Customer demands can also change. The resulting complexity and unpredictability make maintaining high delivery reliability more difficult. (Stevenson et al. 2005; McKay & Wiers 2004, p. 20, 38-39, 225-226; Amaro et al. 1999; Sharp et al. 1999.)

The objective of this study is coming up with a good way to analyze the current state of delivery reliability and identify ways to improve it. The need for this arose in a project that aimed to find the most important root causes of delivery date postponements in a company and suggest measures for improving its situation.

The problem was first approached by gathering data from past deliveries, categorizing perceived problems and analyzing the data with statistical methods. This approach soon turned out to be unsuited for such a complex problem. Categorizing the data was a highly subjective and inflexible task, and didn't enable considering the interrelationships between the different issues. This had a negative effect on the reliability of the analysis. In addition, the method didn't lead to finding the most important root causes or notably help coming up with improvement measures. Therefore, another way of analyzing the situation was needed. This study presents that new way.

As the goal of this thesis is developing a way to effectively analyze the situation in a company, the main research question is

- How to plan and execute a current state analysis in a delivery reliability improvement project?

The following, more detailed questions support answering the main question:

- How to gather relevant data for the analysis?

- How to model the current state of a complex situation?
- How to verify the model of the current situation?
- How to identify opportunities for improvement?

This thesis is carried out as a case study and it uses the constructive research approach. It means that a construct is produced during the course of study (Lehtiranta et al. 2015). The construct in this case is an improvement method for carrying out a current state analysis and finding ways to improve the situation. As the motivation for creating the new method was that the initial approach was not fitting, the new approach must avoid the same pitfalls. Therefore, it must be able to model the situation without oversimplifying it and especially without obscuring interrelationships between different factors. It must also be able to direct attention to the root causes of problems concerning delivery reliability and assist coming up with improvement measures.

The improvement method is based on combining understanding from literature and interviews into a cause and effect chart. The literature reviewed for this work is about factors that generally affect delivery reliability. The interviews are needed to gather a comprehensive understanding of the situation. This should also include the tacit knowledge that the employees of the company possess.

The cause and effect chart is analyzed using ideas from systems thinking. It is an approach to better understand and to improve social systems. A wider perspective is taken in order to see the big picture behind individual occurrences. Problematic situations are approached by studying the relationships between the elements of the system rather than dividing the system into pieces and analyzing them individually. (Reynolds & Holwell 2010, p. 7-8; Senge 2006, p. 68-69.) System dynamics is especially important for this study. It provides a way of modeling a situation so that the relationships between elements in the system become visible (Morecroft 2010, p. 25; Senge 2006, p. 166). In this thesis, it is used for analyzing the generated cause and effect chart by searching for vicious cycles in it. The suggested improvement measures are chosen so that they can break these cycles.

The constructed improvement method is implemented in the company, which produces complex, customized products in small series. Because the results in the company's case are confidential, they will not be presented in this thesis. Instead, hypothetical examples are used to demonstrate the functioning of the generated method.

The remainder of this thesis is organized as follows. Chapter 2 reviews literature relating to carrying out a current state analysis. This includes the basic principles of systems thinking, mainly soft systems methodology and system dynamics, methods for tacit knowledge elicitation and ways for visualizing interdependencies in a complex situation. Chapter 3 gives an overview of relevant literature relating to delivery reliability. This includes literature on production planning and control, supply chain management, lean manufacturing and agile manufacturing. Chapter 4 explains the research questions and boundaries and describes the chosen research strategy and methods. Chapter 5 introduces the improvement method and describes its use in the case company. Chapter 6 is a discussion of the feasibility and generalizability of the method and its connection to theory. Chapter 7 is the conclusion, including a summary of the answers to the research questions.

2. THEORETICAL BACKGROUND FOR CARRYING OUT A CURRENT STATE ANALYSIS

To be able to sensibly intervene in a situation, one must have a clear picture of what it is one is intervening in. This means understanding the factors that dictate the everyday operations in the situation. (Checkland & Poulter 2010, p. 201.) A current state analysis describes the present state of a business process. Preparing one is helpful when there are known issues in the current state or when wishing to streamline a process. A current state analysis documents the way the process currently runs, including its shortcomings. Stakeholders from all relevant roles in the process should be included in order to gain a comprehensive understanding. (Brandenburg.)

This chapter reviews literature on theory that is necessary for carrying out a current state analysis in order to improve delivery reliability in a company. Systems thinking offers a way of examining a complex situation and seeing what structures cause the perceived occurrences. It also introduces a way of visualizing those structures. Tacit knowledge elicitation is needed to gain a thorough understanding of the situation from the people in the relevant roles. Common ways of visualizing cause and effect relationships are reviewed to gain ideas of how to model the situation.

2.1 Systems thinking

Systems thinking is an approach for better understanding and improving social systems (Aronson 1996). It is applied to bring clarity to altering, complicated structures (Checkland & Haynes 1994). A system, as regarded in systems thinking, is goal driven, transforms inputs into desired outputs in a purposeful way and includes performance measures. It exists in a defined environment that influences its operation. (Wastell 2012.) Checkland and Poulter (2010, p. 202) describe a system as an adaptive whole, an entity that evolves according to changes in its environment. A system consists of subsystems and thus has a layered structure.

Systems thinking is a powerful approach for addressing so called wicked problems. They are problems that can’t be solved by directly applying a scientific theory and most times don’t even have an optimal solution. They are social issues that can never be fully and conclusively solved because of such things as conflicting political requirements, complexity or ambiguity of objectives. Often just defining the problem can be difficult. (Rittel 1973.) Reynolds and Holwell (2010, p. 15) suggest three motivations for adopting systems thinking: understanding interrelationships, dealing with different perspectives and addressing power relationships.

Systems thinking is founded on the idea that complex systems are characterized more by their structure than their individual parts (Reynolds & Holwell 2010, p. 8). The traditional approach of dividing a problem into smaller pieces obscures the interrelationships between those pieces and thus makes it harder to make improvements to the system as a whole (Senge 2006, p. 3).

Systems thinking offers a way of looking at things from other people's perspectives to see the big picture behind perceived individual occurrences. Instead of dividing the system into smaller units and analyzing them, systems thinking aims to study the relationships between the elements of the system. (Reynolds & Holwell 2010, p. 7-8.) So, problematic situations are approached in the opposite way to the traditional approach: instead of dividing the system into smaller and smaller parts, a wider and wider perspective is taken (Aronson 1996).

2.1.1 Understanding a complex situation

Complex systems are characterized by numerous interrelationships, constant change and the related uncertainty, and the people in it having differing perspectives. (Checkland & Poulter 2010, p. 192; Reynolds & Holwell 2010, p. 8-17). Often past attempts to improve them have failed to bring about lasting change, or have even made matters worse. The interrelationships mean that actions in the system affect the environment around it, and the environment affects the actions. There is typically no obvious solution to a complex issue. (Aronson 1996.)

There are many limitations in the traditional way of looking at things. Interconnections between factors are often ignored, leading to unintended consequences when attempting to change the situation. It is assumed that there is one root cause behind a perceived problem. Not considering the structures behind an identified root cause can lead to blaming an individual, who was making logical decisions from their own point of view. According to the systems thinking philosophy, no single person is responsible for a problematic situation in a complex system. Instead, the responsibility for problems generated by a system is shared by all the actors in it. (Reynolds & Holwell 2010, p. 8; Senge 2006, p. 20, 78.)

So-called hard systems, even large and complex ones, like a paper machine or a power station, can be addressed using straightforward methods, such as mathematics. Systems engineering deals with such hard systems. (Checkland & Haynes 1994.) They display so called detail complexity, which is complexity arising from having many variables (Senge 2006, p. 71). The opposite of such hard systems are soft systems, where problematic situations can't be approached by modelling or optimization. Often it isn't even obvious what the problem is. The Soft Systems Methodology (SSM) was designed for addressing such “messy real-world situations”, which are common in management. (Wastell 2012.) They display a different kind of complexity, called dynamic complexity. It is present in situations where cause and effect relationships are subtle and the effects over time are uncertain. (Senge 2006, p. 71.) SSM is based on systems engineering, but unlike it, considers the differing worldviews that people have, which greatly affect their behavior. Worldviews describe how people view the world and the criteria they use to judge whether a situation is good or bad. SSM considers human interactions and the complexities arising from them. Compared to systems engineering, it is thus better suited for dealing with complex social issues. (Checkland & Poulter 2010, p. 196-201.)

SSM recognizes that in situations perceived as problematic, there are usually people operating who take purposeful action from their own perspective. There are as many interpretations of the situation as there are people observing it, and the system might look completely different from the various perspectives. The decisions that people make are usually logical from their point of view, even if they appear to be something else, like laziness, from some other perspective. (Wastell 2012; Checkland & Poulter 2010, p. 192.) Surfacing the different perspectives present in a system is a major strength of SSM (Reynolds & Holwell 2010, p. 18).

Another branch of systems thinking, and especially interesting in regard to modelling a situation, is system dynamics. It is an approach to help understand the underlying structures that influence how a system works (Senge 2006, p. 166). This is achieved by visualizing the interactions of the elements of the system. (Morecroft 2010, p. 25.)

The underlying structures that dictate the behavior of a system are often not obvious (Morecroft 2010, p. 26). This leads to seeing the behavior of the system as a given, something that one can’t influence. This can cause a strong sense of powerlessness. (Senge 2006, p. 77). However, often situations that appear random to someone within the system are consistently caused by the structure of the system. The aim of system dynamics is making these structures visible by widening the perspective that is used to view the situation. This requires giving up the pragmatic and very common event-based mindset. An event-based mindset means that events are seen as being caused by other, clearly identifiable events. An associated notion is that problems can be fully fixed by pinpointing the root cause and applying the right solution. In contrast, system dynamics sees problems and solutions as being interrelated, so that one problem can’t be fixed without influencing other parts of the system. (Morecroft 2010, p. 26-28.) Having too simplistic of a picture of a situation leads to applying symptomatic solutions, a.k.a. short-term fixes to alleviate immediate problems, which do nothing to improve the underlying conditions that cause those problems. The symptomatic solutions have a tendency to generate a need for even more short-term fixes, so that the situation might even deteriorate in the long run. (Senge 2006, p. 14-15.)

Seeing linear event chains means seeing only a part of the structure. Feedback loops in a system mean that the elements of a system influence each other in such a way that the consequences of an action eventually come back to the actor itself. (Senge 2006, p. 74-77.) An example of a feedback loop can be seen when someone in a complex system attempts to change their situation. When the improvement attempt affects someone else, they will take action of their own to correct against the change they have experienced. This in turn will feed back to the first actor's situation, who will take further corrective action and so on. Both might feel that the perceived problems are out of their control. It is the change to a wider perspective that would help them see how their own actions cause the system to perform the way it does. (Morecroft 2010, p. 30-31.) A central message of system dynamics is thus that the reality we perceive has been created by our own actions (Senge 2006, p. 220).

Feedback loops are visualized with causal loop diagrams. They show causal links between variables. The influence can be in the same direction (when A increases, B also increases) or in a different direction (when A increases, B decreases). Delays between cause and effect are also visualized. (Senge 2006, p. 73-91.)

There are two basic types of feedback loops: reinforcing and balancing (figure 1). Reinforcing feedback loops amplify the current direction of the process, whether growth or decline, as a snowball effect. Vicious cycles are reinforcing loops taking the system into an undesired direction. If it is possible to reverse them, they can turn into virtuous cycles, which are reinforcing loops of positive development. (Senge 2006, p. 79-83; Meadows 1999.)

In most systems, the process can't keep growing or declining forever. A balancing feedback loop will eventually kick in and stop the amplification. Balancing loops resist change to the current situation, working to maintain some goal or target, which is often unspoken. People acting in the system might not be aware of this implicit goal even though it influences their decisions. (Senge 2006, p. 83-88.)

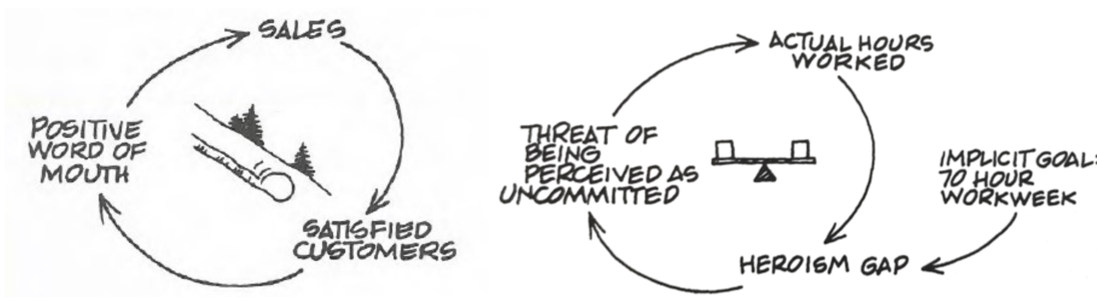

Figure 1. *A reinforcing feedback loop (left) and a balancing feedback loop (right) (Senge 2006, p. 81, 85).*

The left image in figure 1 describes a reinforcing loop where success feeds success. A good product is sold, leading to satisfied customers, who share their positive experience, leading to more sales. The right image describes a balancing loop where the work hours of a company's employees trend towards 70 hours a week, although this goal has not been explicitly expressed. This implicit goal works to keep the state of the situation like it is, even if attempts are made to avoid overworking. (Senge 2006, p. 81-86.)

Delays between actions and their consequences are a major factor hindering the recognition of causal relationships. When people don't see the results of their actions and decisions, they can't learn from them. The effects are especially difficult to see if it takes a year or more for the results of an action to come back to the actor. (Senge 2006, p. 23-24.) Delays tend to cause oscillations and both over- and understeering (Meadows 1999).

As an example of delayed feedback, Repenning et al. (2001) found that fire-fighting efforts in product development lead to the need of even more fire-fighting later. Fire-fighting in this case means allocating resources to solving big, immediate problems. People solving the short-term problems of a project near its deadline consequently have less time to plan the next project. The next project will then need to be rescued when its deadline approaches months or years later. The authors noticed that there is a certain amount of upfront work which needs to be completed on time for fire-fighting to remain an isolated phenomenon. Past this tipping point, the requirement for firefighting efforts will keep increasing until there is minimal time left for routine working. The delay between the resource allocation away from a project and the firefighting it needs later makes this cause and effect relationship difficult to see. So, companies often reward those that successfully save projects from disasters, even though it will lead to other disasters further down the line.

Senge (2006, p. 91-112) introduces the idea that even the more complicated issues faced by organizations follow certain rather simple patterns which are built up of the basic types of feedback loops and delays. They are called systems archetypes, and variations of them are found again and again in different kinds of situations. They help seeing the systemic structure behind a problematic situation and suggest ways to improve them.

From the point of view of delivery reliability, an interesting example of a systems archetype is the eroding goals structure, presented in figure 2. It displays the behavior where a long-term goal is let decline just a little in order to meet a short-term goal. Gradually the long-term goal could deteriorate considerably, far more than would have been accepted initially. (Senge 2006, p. 22-23, 394.) The business case example Senge (2006, p. 394-395) gives for such a structure is of a company that loses market share despite a brilliant product, because delivery times have deteriorated to uncompetitive levels. This has been caused by making delivery times longer when meeting schedules was difficult. The fire-fighting example could also be seen as an example of the eroding goals systems archetype, as the immediate short-term goal of finishing one project erodes the goal of preparing for the next (Repenning et al. 2001). Senge's (2006, p. 394) suggestion for such cases is holding on to the original vision.

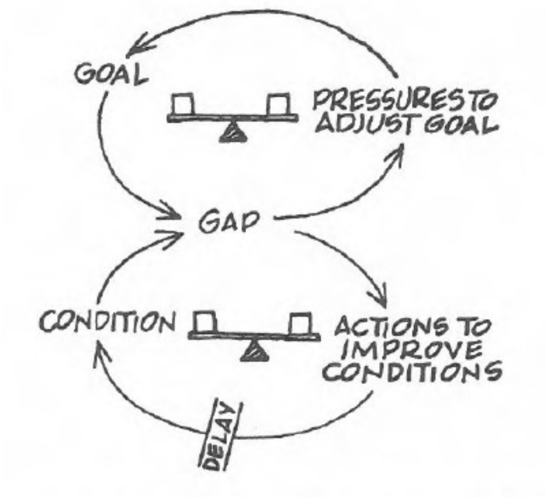

Figure 2. *The eroding goals pattern (Senge 2006, p. 394).*

Another major theme in system dynamics is mental models. They are conceptions a person holds that are based on their values and previous experiences. They are usually not communicated and the person might even be unaware them, but they guide people's thinking and actions nonetheless. It is necessary to make them visible, as they are most dangerous when people are unaware of them and their impact on their actions. (Senge 2006, p. 161-166.) For example, it is common that people see only their own role in the organization as being their responsibility, and don't consider the consequences their decisions might have elsewhere (Senge 2006, p. 18-19).

2.1.2 Improving a complex situation

Wicked problems, the kind that systems thinking addresses, can't be solved with the same kind of mindset as typical engineering problems. This is because there are no right or wrong solutions, just better or worse. In addition, often what is better and what is worse depends on perspective. One way to describe a problem is considering it as the difference between the real situation and a desired situation. (Rittel 1973.)

Wicked problems can be considered to be symptoms of other, higher level problems. Thus, solving the higher-level problem would also solve the resulting lower level problems. Unfortunately, the higher the level of the problem, the more difficult an intervention usually is. With such complex problems, the effects of a solution can't be tested beforehand and no two cases are exactly alike. (Rittel 1973.)

When dealing with complex situations, it is often not clear what the problem is in the first place (Reynolds & Holwell 2010, p. 8). Checkland & Poulter (2010, p. 191-192) discourage using the word problem, as this implies that there is a clear entity that can be solved. Instead, systems thinking aims to improve a situation that is seen as problematic.

It is quite common in the business world to go about solving a problem by addressing the visible symptoms, but this will usually only improve the situation in the short term. In the long term, such localized solutions might even make matters worse. This is why it is important to look for the underlying structures behind the issue. (Senge 2006, p. 14-15.) To address complex issues, one must consider the whole system rather than only looking at it from one's own perspective. As discussed earlier, according to systems thinking the functioning of a system depends on its structure rather than its individual parts. Thus, sustainable improvement to the system must come from addressing its structure. (Senge 2006, p. 68-69.)

Reynolds and Holwell (2010, p. 17) recommend implementing three purposeful orientations when intervening in a system. These are making sense of the relationships between entities in the system, surfacing contrasting perspectives and exploring power relations, boundaries and conflicts between entities and perspectives.

SSM is an action oriented approach for organizing thoughts about a situation so that it can be improved. The basic idea is to generate actions for improvement through the process of learning about the situation. The SSM methodology uses a guideline for addressing problematic situations. Conceptual models of the system are built to capture the differing worldviews that guide people's actions. They are then used as a basis for discussion to bring about change that all parties can accept. Consensus on the action to be taken is usually not reached, nor is it expected. (Checkland & Poulter 2010, p. 192-194.)

The suggested guideline for implementing SSM in a complex situation is the following seven-stage approach by Checkland (1981, p. 163):

1. Problem situation unstructured
2. Problem situation expressed
3. Root definitions of relevant systems
4. Conceptual models
    a. Formal system concept
    b. Other systems thinking
5. Comparison of 4 with 2
6. Feasible, desirable changes
7. Action to improve the problem situation

Phases 1 and 2 aim to build a comprehensive picture of the situation. The first stage is finding out about the situation without trying to fit it into any structure. The second stage is clearly expressing what the situation is. The expression should be neutral. Note that it is the situation that is described, not the perceived problem. Many different people's perspectives should be included in these stages. In phase 3, the systems that seem relevant to the situation are identified and explicitly expressed in normal language. It is suggested that the expression takes the form input – transformation – output. In stage 4, conceptual models are made of these defined systems. Stage 3 described what the relevant systems are, and stage 4 describes what they do. The description is not of the real system, but rather of the steps that are logically required to achieve the transformation that takes place in the system. This can be done e.g. by using the principles of system dynamics. In stage 5, the systemic description from stage 4 is compared to the description of the real situation from stage 2. The purpose is to generate discussion based on the differences between this conceptual model and the real situation. In stage 6, feasible, desirable changes are suggested based on the discussion. Changes can be directed to structures of the system, to procedures or to attitudes. Stage 7 is taking action to improve the situation, in the direction defined in stage 6. (Checkland 1981, p. 162-181.)

The process of using the seven stages is very flexible in order to be able to adapt to the complexity of the real world and the uniqueness of human situations. All stages don't have to be completed every time or used exactly in order. Rather, the steps provide a guideline from which the user can implement the parts best suited for their case. Many steps can be worked on simultaneously. Backtracking and iteration are often necessary. It is not unusual that the focus of the intervention changes during the process. (Checkland & Poulter 2010, p. 202, 207-208; Checkland 1981, p. 162-163.)

The structural behavior of systems that causes short-term solutions to fail also means that changing the system in the right place can bring a major improvement with a relatively small action. The way to create lasting improvement is finding the place where such behavior can be achieved. This principle is called leverage. Places of high leverage are ones where small change can bring a big impact. They are often not obvious and can even be counter-intuitive. This is because of the same phenomena as why the underlying structures are difficult to see: the effects of actions might take a long time to become visible, and the results might appear in a completely different place than where the action was implemented. (Senge 2006, p. 63-64.)

Causal loop diagrams help in understanding the cause and effect relationships in a system and gaining the shift of mind that is needed to understand the functioning of the entire system (Morecroft 2010, p. 43). The systems archetypes introduced in system dynamics offer a way of changing the way a system functions. Identifying a systems archetype suggests areas of high- and low-leverage change. (Senge 2006, p. 93-94.)

Meadows (1999) presents a twelve-point list of places to intervene in a system. These are places of high leverage. In order of most to least effective, they are

1. Transcending paradigms. This means staying flexible by realizing that no paradigm or mindset is "right" and choosing the one that best fits the situation.

2. Changing the paradigm behind the goals, structure, rules, delays and parameters of the system.
3. Changing the goals of the system. They guide the way the system is structured and what actions are taken. Often the goals are not consciously understood.
4. Power to add, change, evolve or self-organize the system structure. This is dictated by the ways the system can add or subtract on itself and test new patterns in an evolutionary manner.
5. Changing the rules of the system. They are what set the boundaries of the system, limiting the flexibility of its performance and the actions that can be taken.
6. Changing the structure of information flows. Providing information to actors who didn't have it before is in effect introducing a new feedback loop. Further, it is argued that missing information is one of the most common causes for systems to not work like they are supposed to. Being informed about the effects of one's actions increases accountability.
7. Weakening self-reinforcing feedback loops. They will eventually run into a limit that will decrease the amplification, but letting harmful loops run their cause can cause a lot of trouble before that limit is reached. Some powerful reinforcing loops could even destroy the system.
8. Changing the effect of balancing feedback loops. This is in relation to their strength compared to the changes that they correct against, their accuracy and the speed of the feedback.
9. Changing the length of delays. If there is a delay in the system that can be controlled, the impact could be significant. Unfortunately, the length of delays is often very difficult to change. Often it is easier to slow down the process that the feedback loop is trying to control than shorten the delay.
10. Changing the physical stock-and-flow structure of the system. Once a design is built, changing it is often very difficult or even impossible. Attention should be paid to limitations and bottlenecks, while avoiding fluctuations or straining the system's capacity.
11. Changing the sizes of stabilizing stocks. Big buffers stabilize a system, but simultaneously make it inflexible.
12. Changing constants, parameters and numbers that affect the rate at which things happen in the system, but don't fundamentally change how it operates.

Generally, more leverage can be found in affecting the information and control parts of the system (points 1-8) than the more physical aspects of it (points 9-12). (Meadows 1999.)

Systems thinking aims to bring about long-term rather than short-term improvement. Unfortunately, fundamental solutions tend to display a worse-before-better structure, whereas symptomic solutions usually display a better-before-worse behavior. The delay makes it difficult to see the causal relationship. (Senge 2006, p. 103-112.) Making delays between cause and effect as short as possible, which enables people to learn from their actions, is one of the most effective ways for improving the performance of a system (Senge 2006, p. 88).

2.2 Tacit knowledge elicitation

Rarely does an individual person have enough knowledge to solve a complex problem alone. Often people are expected to search through databases and other formal documentation for more information, but in many cases, this is not the most effective way of gaining relevant information. Instead, other people often hold the most useful knowledge. (Koskinen et al. 2002.) As discussed previously, the functioning of a system depends on the actions that people take that are sensible from their own perspective. It makes sense, then, that to understand the current state of a situation, one would turn to the people in it to find out about how they act and why.

2.2.1 What is tacit knowledge?

Traditionally, Western cultures have considered knowledge to be justified, objective truths. However, the knowledge that people possess can't be free of human subjectivity. People have differing visions and mental models that define the context of the knowledge they hold. This kind of personal, subjective and context-specific knowledge is called tacit. (Bratianu & Orzea 2010, Nonaka et al. 2000.) It is difficult to formalize and communicate to others. People are often unaware of the tacit knowledge they possess or think it is common knowledge. This means that people know more than they can tell. (Desouza 2003; Neve 2003; Polanyi 1997, p. 142.) The opposite of tacit knowledge is explicit knowledge, which can readily be expressed in words or e.g. mathematic formulas. (Desouza 2003.)

According to Ambrosini and Bowman (2001) knowledge can be situated somewhere on a spectrum between fully explicit knowledge that can be communicated easily, and fully tacit knowledge that is so deeply ingrained that it is totally inaccessible. Tacit knowledge can also be the kind that could be accessed by asking the right questions. This kind of knowledge includes understanding and skills that people have acquired over time and can now use without thinking about it. If they were asked how they do a specific task, they could express this tacit knowledge. There is also tacit knowledge that can't be expressed with normal language at all, but could be articulated using some more creative ways, such as metaphors or storytelling. (Ambrosini & Bowman 2001.)

There are two components of tacit knowledge, a technical and a cognitive component (Bratianu & Orzea 2010). The technical component includes the skills and know-how of the person and is rooted in the routines and rules-of-thumb that people use in their everyday work. The cognitive component consists of their subjective insights, values and perceptions. (Bratianu & Orzea 2010; Carlile 2002; Nonaka et al. 2000.) Eraut (2000) uses a similar division and distinguishes between tacit understanding and tacit knowledge in action. Tacit understanding includes the way people view others and interpret their actions based on previous interactions, and how they see the organization's culture. Tacit knowledge in action means the routinized activities that one doesn't have to think about when performing them. This does not only refer to simple repetitive work, but also complex cognitive skills like decision-making.

2.2.2 Transferring tacit knowledge

To be able to use tacit knowledge, it must be made explicit (Desouza 2003), and for explicit knowledge to be useful, tacit insights are needed (Nonaka et al. 2000). According to Nonaka et al. (2000), knowledge is generated when the two types of knowledge interact. They divide the kinds of interaction into four modes, which are socialization (tacit to tacit), externalization (tacit to explicit), combination (explicit to explicit) and internalization (explicit to tacit). As the focus in this study is on gaining insights to use in the current state analysis, it is externalization, the process of converting tacit knowledge into explicit knowledge, that is of particular interest. The authors (ibid) suggest using metaphors, analogies and models to aid this process. Motivation is also an important factor (Bratianu & Orzea 2010).

People interpret information against the social, cultural and historical contexts that they live and operate in. These contexts are no more static than knowledge, but rather depend on space and time. For externalization to happen, participants need to share the context and "speak the same language". Face-to-face interaction supports this. (Nonaka et al. 2000.) It is considered the richest method of transferring knowledge, as it allows immediate feedback and thus prevents misunderstanding. In face-to-face communication, there are more ways to convey meaning, such as body language or tone of voice. (Koskinen et al. 2002.)

Sharing tacit knowledge through dialogue can happen through deliberate or emergent mechanisms. Deliberate knowledge sharing takes place in organized situations such as interviews or brainstorming sessions, whereas emergent knowledge sharing occurs more or less spontaneously in an informal setting. For people to really share their experiences they must be motivated to do so and not feel pressured. (Desouza 2003.) According to Eraut (2000), tacit knowledge is captured by either facilitating the situation so that the person with the tacit knowledge becomes aware of it and can tell it, or by gathering enough information to be able to infer the nature of the knowledge. Dialogue is an efficient way for learning about other people's views (Bratianu & Orzea 2010). An informal setting can encourage people to share even the more "risky" views that they hold, which they could not express in a formal setting (Eraut 2000).

Interviews have been recommended as a good method for capturing tacit knowledge (Karhu 2002). In an interview situation, using appropriate questions can help a person express tacit knowledge. Such question could be of the form “What do you mean by…”, “Could you give an example of…” or simply “Why?”. (Neve 2003.) However, Yin recommends asking “why” questions in “how” form, as “why” questions can cause defensiveness in the interviewee. Generally, interview questions should be friendly and non-threatening. (Yin 2009, p. 107.)

Neve (2003) introduces a toolbox for eliciting tacit knowledge in an interview, advising the interviewer to repeat, verify and concretize what the interviewee has said and ask them to give examples of the situation. She recommends letting people describe their experiences as well as letting them consider other people’s perspectives when transferring more personalized knowledge. The interview should be held in a setting that is familiar to the interviewee, as the surroundings can then work as cues (Ambrosini & Bowman 2001), and a venue of the interviewee’s choosing can make the situation more relaxed (Whyte & Classen 2012). Trust between the interviewer and the interviewee is very important for allowing tacit knowledge to be shared (Karhu 2002). The trust is based on the expectations people have of each other, which in turn depends on how they perceive each other’s motives and abilities (Koskinen et al. 2002).

Ambrosini and Bowman (2001) recommend the self-Q technique for eliciting tacit knowledge. It is a self-interviewing technique where the interviewee asks themselves questions about the topic at hand. The relevant concepts are then extracted from these questions. The idea behind the technique is that people are themselves experts on what guides their behavior and they will formulate the questions based on their own view of the situation. One clear advantage of this technique is that the interviewer can’t influence the interviewee’s responses.

Another approach that Ambrosini and Bowman (2001) suggest is semi-structured interviews, where the interviewees are encouraged to tell stories. Storytelling has been suggested as an especially powerful method for tacit knowledge capture. It makes complicated ideas understandable and intelligible. It comes naturally to most people and can prompt a situation where one story leads to another. (Whyte & Classen 2012; Wah 1999.) While telling stories, people often say more than they normally would. Storytelling can be prompted for example by asking the interviewee to tell one positive and one negative story of what has previously happened in the company regarding the topic under discussion. (Ambrosini & Bowman 2001.) The details and context of the story are also important to consider. If the interviewer is not sufficiently familiar with the topic being studied, there is a risk that the documentation of the interviewee’s responses lack specificity (Neve 2003.)

Metaphors and analogies can prove useful with topics that are especially difficult to express in language. (Neve 2003.) They are like an image that can transfer a large amount of data. Metaphors are especially useful for articulating complex, ambiguous experiences and abstract ideas. However, they should not be used when more direct expression would be possible. (Ambrosini & Bowman 2001.) Drawings and other non-verbal methods can also capture tacit knowledge that is difficult to express in language (Koskinen et al. 2002). Having a picture, graph or other such mediating object can support people to tell about their tacit knowledge in more explicit terms (Eraut 2000).

2.3 Visualizing interdependencies

A key part of the current state analysis will be modelling the situation, including the cause and effect relationships between the different factors in it. Some ways of visualizing cause and effect relationships are reviewed in this section.

One common tool for identifying potential causes to a defined problem is the fishbone diagram, also called the cause and effect diagram or the Ishikawa diagram. The idea is to visualize all possible causes and organize them into major categories. The process helps people systematically come up with ideas and assign the direction of causality correctly. (Stern 2015, p. 51; Kollengode 2010.)

The problem or effect to be considered is defined and written on one side of the diagram. A horizontal arrow, “the backbone”, is drawn pointing to the effect. The main categories are drawn as lines stemming directly from the “backbone“. One option for choosing the major categories that is often used in manufacturing is the four M’s: materials, machines, manpower and method. More specific causes are then added to these main bones, as displayed in figure 3. (Stern 2015, p. 51-52; Kollengode 2010.)

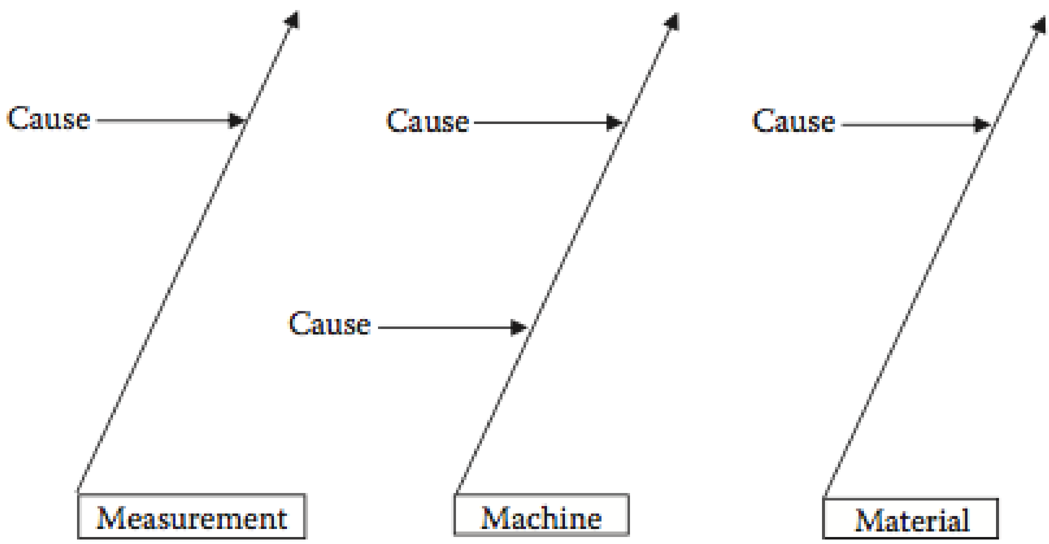

Figure 3. *Format of a basic fishbone diagram (Stern 2015, p. 52).*

The Fishbone diagram is usually constructed in brainstorming groups (Stern 2015, p. 51). Kollengode (2010) suggests techniques like the 5 Whys, causal trees or different root cause analysis techniques for discovering reasons behind the problem. He also recommends focusing on areas where the people building the diagram have influence or control. This provides a place to stop looking for potential causes and helps coming up with meaningful solutions. Looking up data is proposed as a way to confirm the nature of the causes. Bessant recommends verifying possible causes by collecting data, e.g. with checksheets, and analyzing it using Pareto analysis, graphs etc.

Ambrosini and Bowman (2001) suggest a similar technique, causal mapping, for studying tacit skills. Causal maps are graphs consisting of nodes, which represent constructs believed to be important, and arrows linking them, showing the relationships between the constructs. There are many ways of building such a map, e.g. based on checklists, interviews or group discussions. When using causal mapping for tacit knowledge elicitation, it is beneficial to do it as a group exercise. It is suggested that the mapping process is started with a broad question. Causal maps are a good way of analyzing ambiguous situations, as they allow including multiple explanations to things and showing interrelationships between different factors. Causal mapping also enables eliciting tacit knowledge, as people are continuously asked to reflect on their behavior and why they do what they do. This can make unspoken skills visible, thus turning tacit knowledge into explicit knowledge. (Ambrosini & Bowman 2001.)

Juuti and Lehtonen (2010) analyzed dependencies and challenges in decision making of a mobile device developer. To this end, they built a systemic cause and effect chart to model the impacts different elements have on properties of new product development. The elements identified in the case were mapped out and arrows drawn between them to visualize the dependencies. This approach helps identify and visualize what aspects are important for the end goal. Kopra and Juuti (2016) also use the systemic cause and effect chart in order to identify company-specific project success factors. The chart shows relationships between aspects that affect project success and helps identify root causes behind problems. The identified causes were categorized in order to show that different kinds of causes require different approaches for resolving them.

3. FACTORS AFFECTING DELIVERY RELIABILITY

This chapter introduces the theoretical background relevant to delivery reliability.

Literature on production planning and control was considered essential, as ensuring delivery date adherence is one of its key functions (Stevenson et al. 2005). The whole supply chain affects the performance of a company (Jahnukainen et al. 1997, p. 10), so supply chain management is included in the review. Short and reliable throughput times are beneficial for delivery reliability (Nyhuis et al. 2005). Lean manufacturing can be used to achieve them through eliminating waste and making production flow (Liker 2004). Agile manufacturing is an approach for prospering in the rapidly and unexpectedly changing business environments, which tend to make production planning and control difficult (Gunasekaran 1999).

3.1 Production planning and control

Delivery date adherence is one of the most important goals of production planning and control (PPC) (Stevenson et al. 2005). Of course, delivery reliability doesn't rely solely on PPC activities, as the production planners and controllers do not have full control over what goes on on the factory floor. Still, they do have a big impact on how well due dates can be met. Unsatisfactory PPC can undermine the performance of an otherwise well-functioning system, while good PPC can compensate for problems caused elsewhere. (Lödding 2013, p. 2; McKay & Wiers 2004, p. 82.)

McKay & Wiers (2003) describe planning, scheduling and dispatching as the key tasks of production control. Production planning means the long-term, higher level planning considering the general capacity, whereas scheduling is the shorter-term, fixed-capacity planning that often handles smaller units than production planning (McKay & Wiers 2004, p. 16). Dispatching deals with the current situation on the factory floor. The way these assignments are realized varies greatly from company to company and giving a clear definition of them is difficult. (McKay & Wiers 2004, p. 36-37.) Therefore, the term production planning and control is used in this thesis to encompass all the different activities.

Typical tasks of production planning and control include scheduling and sequencing of jobs, designating resources to incoming orders, triggering required purchase orders, capacity planning and reacting to unexpected disturbances. Since PPC has to consider so many different aspects (parts and components, resources, processes), this activity spans over organizational boundaries. (Wiendahl et al. 2007; Stevenson et al. 2005.)

3.1.1 Effective production planning and control

Ideally, production planners and controllers should have as few interruptions as possible. Their work is problem solving rather than just mechanical execution, and making good plans requires concentration. (McKay & Wiers 2004, p. 43-46.) Throughout their book, McKay and Wiers (2004) emphasize that avoiding future troubles or, if this isn't possible, mitigating their effects, should be a major part of PPC personnel's work. This, however, requires time, which is often needed for running the other tasks. (McKay & Wiers 2004, p. 34-36, 43-46, 65-69).

A good understanding of the processes in the factory is very beneficial for production planning and control, so planners and controllers tend to be well aware of what is going on in the system. Unfortunately, this means that they are often required to solve all kinds of problems, some of which might not even be related to the actual planning and controlling. These include such activities as searching for lost inventory, tracking engineering changes, expediting shipments and answering questions that people in other positions have. Having the production planners and controllers help others makes sense, because they are usually well equipped to effectively answer the questions and sorting out the problems that the others may have. Still, these distractions might constitute much of the production planners' and controllers' day. This means that there is less time available for making plans and even less for preparing for future troubles. Even more disruptive are the more major problems that might arise in production and take more than a moment to sort out. Furthermore, these kinds of unexpected tasks are usually not considered when determining the resources of PPC departments. One production planner and controller might be responsible hundreds of orders, which makes it impossible to address each one effectively and proactively. (McKay & Wiers 2004, p. 30, 43-55, 66, 221-222.)

Planning and controlling one area of production is deeply dependent on the other areas. Because of this, the process can't operate very efficiently if production planners and controllers only focus on one thing at a time without considering other areas. Furthermore, decisions made in one part of the process will easily cause unexpected consequences elsewhere. This complexity makes it is difficult to show causality between a PPC decision and production performance. (McKay & Wiers 2004, p. 34-41, 84-85.)

One example of a decision that easily has further consequences is resequencing orders in the queue. E.g. Lödding (2013, p. 90) advices to avoid shifting the end date of an order. Unfortunately, it is often unavoidable if production resources are to be kept utilized or the most important orders delivered on time. Prioritizing the most important orders when production is congested will allow them to be delivered on time, but it means that other orders have to be rescheduled too. This makes their production even more uncontrollable, especially if the postponement was a panic reaction. Rushing orders through production with special arrangements on a regular basis can cause major problems in the entire production. Unfortunately, minimizing the impact of the future problems requires time, which production planners and controllers often don't have. (McKay & Wiers 2004, p. 63, 235-236; Jahnukainen et al. 1997, p. 16, 72.)

Impacts on the entire system should be considered before deciding to not finish a job. It should only be done if absolutely necessary and not happen as a spontaneous reaction. If it is necessary to pull a job short, effort should be made to minimize the impact. In such cases the production planners and controllers need to make sure that such occurrences remain isolated and don't become a habit. (McKay & Wiers 2004, p. 235-236, 240.)

Short lead times are an important competitive advantage. There can be considerable temptation to promise them to customers. However, short lead times should not be promised without getting the actual lead times shorter. Over-optimistic estimates can lead to larger inventory as material is brought in too early. The real process will not go like the unrealistic plan, so rescheduling and constant monitoring of exceptions will be required. It can also lead to prioritization of some projects, which in turn will disrupt the production of other orders. Planning should therefore be done realistically. (McKay & Wiers 2004, p. 217; Jahnukainen et al. 1997, p. 8-9.)

Throughput times are sometimes increased in order to improve delivery reliability. This can have the opposite effect than was intended. As throughput times get longer, wait times get longer too. Because of this, there is more time for changes to happen to the order. If working on the order had been started early, the changes will be even more expensive than they would otherwise. It could also be that the order is not started early because it is not yet urgent. Rather, other orders are worked on first. This easily leads to the order being late despite the long throughput time. All this also makes production planning and control more complicated. Shorter throughput times are therefore better for delivery reliability. (Jahnukainen et al. 1997, p. 60.) A further argument for preferring shorter throughput times is that long throughput times increase the likelihood of schedule changes. High delivery reliability requires reliable schedules, but the changes make schedules less dependable. (Nyhuis et al. 2005.)

Another requirement for effective PPC is having a lot of up-to-date information available. Enterprise Resource Planning (ERP) tools are used to handle vast amounts of official information. They often also include tools for PPC. Manufacturing Execution Systems (MES) are used to execute the production plan and gather data from the factory floor. (Järvenpää et al. 2015; McKay & Wiers 2004, p. 8, 11, 18-19, 30-34, 96.) McKay and Wiers (2004, p. 19) argue that implementing a MES tool is essential for properly profiting from the use of information technology. Important benefits of using it are the collection of history data and easier rescheduling. Advanced planning and scheduling

(APS) systems are software that can generate schedules for a value chain or a part of it. They are based on finite capacity planning. With them, schedules can be made quicker and in better quality. They also offer smarter sequencing of jobs. Proper scheduling tools also support planning on a more precise level, which helps with lead time reduction. (Järvenpää et al. 2015.) Excellent PPC also requires information from potential occurrences that could affect production, including ones that might not even seem related production. Production planners and controllers need to know about events that will affect the status quo in order to take them into account. This is one reason why data should not be kept from production planners and controllers. (McKay & Wiers 2004, p. 8, 11, 18-19, 30-34, 96, 224.)

In very problematic situations production planners and controllers should focus on keeping the production running and on "fighting fires". These are cases where matters really aren't in the production planners' and controllers' hands. For example, production tracking could be poor, not allowing for accurate monitoring. Workers might be untrained or machines unmaintained. Such problems are bigger than production planning and control. Better sequencing of jobs or similar sophisticated activities will not be able to solve such problems. Instead, focus should be on improving information flows in order to track the process as well as possible. (McKay & Wiers 2004, p. 33-34, 228-229.)

In most companies, production planning and control has to be split at least to some extent, since the number of products and resources would be far too large for one person to handle. The way the process is set up in a company can be roughly divided into two categories, hierarchical and focused. In the hierarchical model, different departments share resources and have centralized decision making and PPC. The more detailed scheduling is then done on the lower levels. Focused factories have very independent departments that could even be seen as small factories within the factory. They have their own resources, decision making and PPC. It can't be said that one paradigm is better than the other, since the best arrangement is dependent on the situation and can change over time even within the same organization. In any case, the way PPC is realized should correspond to the organization of the physical production. Centralized PPC is the more common approach, since it usually fits the organizational structure of the company. It is characterized by different levels of decision making, by having a master plan to coordinate the production and sales activities and by factory-wide rather than production unit coordination. The focused approach with decentralized PPC has the benefit of reduced complexity within the individual department, as there are then fewer products, resources, and processes to consider. This makes production planning and control more straightforward. (McKay & Wiers 2004, p. 16-17.)

3.1.2 Considering capacity in production planning and control

Having a lot of capacity will make production planning and control easier, as the excess capacity will simply absorb problems. Of course, this is not the case in most companies. Usually there is no excess capacity, delays are penalized and there is little room for error. What's more, having trouble in just one part of the process could cause significant trouble elsewhere in the deeply interconnected network. (McKay & Wiers 2004, p. 31-32.)

Capacity planning is one of the major functions of PPC (Stevenson et al. 2005), and estimating the load of production to match capacity is of paramount importance for delivery reliability. Unfortunately, estimating the load accurately is very difficult, further complicated e.g. by having a wandering bottleneck or several options for producing one part. Not having an accurate estimate can lead to promising due dates that are unattainable. This will result in rushing, overtime and, eventually, delays. (Jahnukainen et al. 1997, p. 71.)

Sato and Tsai (2004) emphasize the integration of scheduling and capacity planning in order to produce feasible production plans. This is because having them separate makes seeing the effects of changes to the schedule very difficult. Production scheduling is commonly done using ERP systems. They define the start date using backward scheduling but without considering capacity. APS, on the other hand, are based on finite capacity and thus generate more viable plans. However, the operations on the job floor have to be well under control for an APS to bring benefit. Industries where using APS has been successful are usually ones with stability and predictability. (Järvenpää et al. 2015, McKay & Wiers 2004, p. 97-98, 103-111.)

As discussed, short throughput times are good for delivery reliability. At the same time, economical objectives require resource utilization to be as high as possible. Short throughput times and high resource utilization are conflicting objectives. This is because high utilization involves high levels of work in progress (WIP), which in turn leads to long and unpredictable throughput times, causing delayed deliveries. Instead of trying to optimize either utilization or throughput times, management must focus on finding a satisfactory compromise between the two. (Nyhuis et al. 2005.)

All resources do not have to always be fully utilized. This will be discussed in more detail in section 3.3.4 regarding production flow. The overall system only benefits from the close management of bottlenecks and the resources feeding them. Performance metrics should reflect this. System-level performance metrics and objectives are necessary to avoid sub-optimization. Producing more than planned is not desirable, as it can cause side effects. If production achieves more than was planned for, the saved time can be used for something else than producing ahead of schedule. Options include cleaning, training or maintenance, or any other task that there hasn't been time for before. (McKay & Wiers 2004, p. 196, 217-218.)

One way of addressing the conflict between resource utilization and throughput times is by order release. It means gathering incoming orders to a pool and defining when production is allowed to start working on each one of them. The release may happen periodically or continually. The criteria for selecting the orders to be released have to be well thought out for the technique to be beneficial. (Bergamaschi et al. 1997.) According to Bechte (1988), order release has a significant impact on due date reliability.

There are different methods of order release. One is having no criteria, so production can start immediately when the order is created. This approach doesn't allow for controlling the amount of WIP or the load at the workstations and thus makes throughput times highly unpredictable. (Lödding 2013, p. 305-306.)

Releasing based on the due date gives production the go-ahead on a certain planned earliest start date. This is the most common method and the one best supported by ERP systems. The downside is that it expects the production program to be followed exactly, so if the realized throughput deviates from the planned throughput for any reason, WIP and throughput times will also not follow the plan and the utilization of resources might be affected. (Lödding 2013, p. 306-308.)

Releasing orders based on the level of WIP lets actual output define the input. In this approach, the go-ahead for an order is given based on a certain predetermined level of WIP. The advantages of WIP based order release include robustness to changes. It makes adjustments more automatically, so that there shouldn't be any need for reorganizing orders when a planned order is postponed or cancelled. It also means that there is less fear of the production resources being idle when it happens. If there are not many changes in sequencing, throughput times will also fluctuate less, making the process more predictable and easier to schedule. This approach makes the process more robust toward varying demand. Because of the strong connection between WIP and overload in a production unit, WIP based order release also helps keep the amount of overload on reasonable levels. This helps avoid bottlenecks and supports prioritizing orders so that capacity is predominantly used on the most important orders. Of course, there are also downsides to implementing WIP based order release. If the amount of WIP should exceed the planned level because of scheduling, further scheduling actions are hindered and the existing plan will become unreliable. When orders are completed early, there is an increase in the capital tied to completed products. (Lödding 2013, p. 308-311.)

One principle for order release considered to be especially effective is load-oriented order release, where the decision to release orders is based on the loading situation of resources (Perona & Portioli 1997). It is very similar to the order release based on WIP levels, as its aim is also keeping the amount of WIP reasonable. This means more predictable throughput times and more reliable schedules while at the same time having high resource utilization. The basic idea of the concept is holding orders back if any of the workstations required for its fulfilment are overloaded. (Lödding 2013, p. 384; Bechte 1988.) A lower workload limit may also be implemented to prevent the workstations from going underutilized. One advantage of load oriented order release in comparison to many other proposed approaches is that it is not as complex to implement, making it easier to balance the workload without affecting throughput. (Bergamaschi et al. 1997.)

3.1.3 Production planning and control in small series production

The engineer-to-order (ETO) approach means manufacturing products that have been designed to meet the customer's specific needs. Offering the customer more options for customization can be a major advantage to a company. The downside is that it results in producing smaller amounts of each product, each with unique material requirements and routing in production. This increases variation and resource complexity, which makes the production process more unpredictable and therefore more difficult to plan and control. Because of this, throughput times and inventory levels cannot be expected to be similar to mass production. (Stevenson et al. 2005; McKay & Wiers 2004, p. 20, 38-39, 225-226; Amaro et al. 1999; Jahnukainen et al. 1997, p. 15.)

Complexity already starts in product development, which defines the high variability and often calls for changes, even after production has already been started. Companies often believe that changes in orders are caused by customers, but in reality, they are most often caused by the company's own processes. (Jahnukainen et al. 1997, p. 22-23, 88.)

Variability, which is typically high in small series construction, consists of variation and variance. Variation describes how many different types of things, e.g. parts, batch sizes, resources or operations, there are. For production planners and controllers, high variation means more options to consider and therefore makes their work more difficult. Variance describes the difference between what was planned and what actually happened. It brings uncertainty to the process. Some variance exists in almost all aspects of manufacturing. It can be planned for by using efficiency, utilization and yield estimates that are less than 100%. High variance is problematic for PPC, as not having reliable predictions of what will happen and how quickly will obviously make it more difficult. (McKay & Wiers 2004, p. 123-125.)

Variability in production will always cause some kind of a penalty, even when production planning and control is excellent. The company will have to compromise between three penalties, which are the buffering of flows, lowered resource utilization or lost production. PPC should look for the solutions that minimize the overall harm from these penalties. (Bertelsen et al. 2006.)

Bertelsen et al. (2006) study ways for managing construction flows. Their findings are well applicable from the point of view of small series production as well, because the challenges faced in the construction industry are very similar. They include variability, one-of-a-kind products and assembly type production. The assembly task of production consists of several input flows, each of which has a likelihood of deviation (Koskela 1999). The important flows to be considered include material flows, but also immaterial flows, such as information, crews, and external conditions, which are all necessary for the process. The interaction between the flows must also be considered. (Bertelsen et al. 2006.) Flow management reduces the impacts of variability and so reduces throughput times. (Koskela 1999). The aim is to identify the slowest flow or combination of flows, which acts as the bottleneck of the whole process (Bertelsen et al. 2006). Bertelsen et al. (2006) recommend the last planner method for reducing variability and its impacts. It consists of five principles: Work should not start until all requirements for its completion are present. The realization of assignments is monitored. When the realization of an assignment has not happened as planned, the causes are investigated and removed. A buffer of tasks is maintained, so if a task is disrupted, another one can be started. And lastly, the availability of prerequisites for upcoming tasks is actively ensured by look-ahead planning with a time horizon of a few weeks. (Koskela 2000, p. 191.)

In order to minimize problems caused by variability, it can be beneficial to divide products into two categories: standard products with a lot of repetition and non-standard products with more customization (Jahnukainen et al. 1997, p. 22). The problems that one-of-a-kind products cause can be mitigated by standardizing the included parts, solutions etc. (Koskela 1999). Thus, modularization offers relief to the problems caused by variability. It moves the need for customization into a further point in the process, reducing variation in the earlier phases. Having fewer parts and components reduces storage levels, increases turnover speed and enhances the performance of purchasing, as there are fewer objects to monitor. (Jahnukainen et al. 1997, p. 22-23.)

3.2 Supply chain management

It is not enough for a production planner and controller to focus on the happenings inside their company, since the whole supply chain affects the situation in it. The supply chain is the network of all the actors involved in bringing a product to a customer, all the way from raw materials up to delivery to the end customer. As the name suggests, supply chain management (SCM) is managing this chain across organizational boundaries, aiming toward better coordination and transparency. Improvements are found through studying the interdependencies in the network. Cooperation is achieved in part by having a small number of suppliers and maintaining a close relationship to them. (Vrijhoef & Koskela 2000.)

If only one party in the supply chain is late, the whole order will be. Therefore, if a supplier is not fully reliable when it comes to holding delivery dates, the next company will have to buffer their production and plan their work on unprecise information, making it more difficult for them to hold their own due dates. Adding a buffer to account for a possible delay in the delivery from the supplier will typically not improve reliability, since suppliers tend to learn quickly how much slack there is in the given delivery times. So, improving the functioning of the supply chain requires cooperation between all parties. This usually includes removing non-value-adding and overlapping activities. Unfortunately, the responsibility for the controlling of the supply chain is usually divided into the different companies, all of them aiming to optimize their own processes alone. This makes the entire chain function less efficiently, just like optimizing individual departments in a company is not the optimum for the entire company. (Jahnukainen et al. 1997, p. 10, 15-18, 41, 61.)

When improving order-based purchasing, it is recommended that the focus lie on punctuality and speed of the delivery rather than decreasing storage levels. The latter would most likely lead to missing materials in the customer company's end. To be able to plan enough capacity to answer to the customer's needs, the supplier must be notified beforehand on future demand. Receiving this information on a regular basis and in a systemized manner, such as on a standardized form, will make the supplier's process run smoother. (Jahnukainen et al. 1997, p. 49-53, 64.) This also improves information transparency by getting rid of the traditional email or phone call based order process. Managing email or phone based orders requires the data to be typed down to the company's information system by hand, which is prone to human error. Some details might not be entered in the system at all, so some people who could benefit from them might not have access to them. (Järvenpää et al. 2015.) Often the customer feels that such a standardized procedure will make the process less flexible, but when there is less need to fix problems caused by random and unorganized communication, the benefits will usually outweigh the problems. (Jahnukainen et al. 1997, p. 49-53.)

The value-adding time while a product moves through the supply chain is often a small fraction of the total flow time, and the lead time is unnecessarily increased when every link in the chain adds a time buffer to their schedule. Problems in the supply chain have often been found to be caused by external parties, by lacking or incorrect information from design, or by delays caused by late or faulty information and inadequate communication. These problems cause further problems in other parts of the supply chain, and the complex, interrelated problems are further aggravated by short-sighted planning. (Vrijhoef & Koskela 2000.)

Planning and controlling the supply chain requires a well-functioning information flow and authority to affect the situation, just like in in-house production planning and control. As is the case with PPC in general, planning and control throughout the supply chain is also easiest with high-volume, low-variation products, few suppliers and customers and matched capacities between them. Less ideal, more complex supply chains are much more difficult to control. The controlling also requires more flexibility and visibility throughout the chain. So, more resources and support are needed for the planning and controlling activities as the complexity in the supply chain increases. (McKay & Wiers 2004, p. 37-39.)

Suppliers base their activities on the information they get from their customers. If the customer company's production planning and control is inaccurate, the delivery times in the whole supply chain will be. Changes made by the customer will inevitably lead to changes at the supplier's end, making their process more volatile. The customer company should not give the supplier more precise information than it has at hand, since forecasts have the tendency to cause disruptions in the supply chain. Minimizing the need for forecasting is one of the many benefits of shortening lead times. Ordering as late as possible should reduce the amount of changes that occur after the order has been placed. This makes the supplier's process more manageable and improves the efficiency of the supply chain. (Jahnukainen et al. 1997, p. 57-59, 64.)

The customer may sometimes make orders that are needed quicker than the delivery time the supplier can normally offer. They need to be rushed through, disturbing the other orders and making their delivery dates less reliable. As a result this decreases the common trust of both parties. (Jahnukainen et al. 1997, p. 46.)

Usually suppliers are allowed to deliver ahead of schedule without consequences. This habit is not unproblematic, as it increases capital tied up in the storage and means more extra work in case of changes in the product structure. (Jahnukainen et al. 1997, p. 62.)

Reducing the amount of suppliers by ordering more parts from the good ones and less from the bad ones makes managing suppliers easier and enables closer relationships to the remaining ones. Still, there are many cases where forming a close relationship to one supplier is not sensible. Having less suppliers for one part will increase dependence on that supplier. Smaller batches from each supplier could mean higher prices and longer delivery times. Sometimes the supplier doesn't even have enough capacity for all their customers, and in this case the customer company must have more suppliers. (Jahnukainen et al. 1997, p. 33-34.)

Improving cooperation between the different parties in the supply chain requires a trusting relationship between them. This in turn calls for open communication about issues, a common understanding of the good of the supply chain, and often a personal relationship between the companies' representatives. The improvement process will usually last several years, but having a good cooperation can bring major benefits, not least to delivery reliability. An active cooperation should be sought with only a limited amount of companies to ensure that there are enough resources to develop these relationships. The companies should be chosen carefully, as changing cooperation partners can be very arduous. (Jahnukainen et al. 1997, p. 68-81.) The first aim of developing the customer-supplier relationship should be on improving the basics before moving on to more sophisticated objectives. They need to be in a good shape before a deeper integration is possible. Having a proper partnership should be seen as the end goal. (Jahnukainen et al. 1997, p. 98-99.)

3.3 Lean Manufacturing

Lean manufacturing is used to improve production processes by eliminating waste (Gosling & Naim 2009). It is based on the Toyota Production System (TPS), developed over time in the 20th century in the Toyota Motor Corporation. It challenged the paradigm of mass production, which was the dominant production philosophy of the time. The philosophy, along with the term "lean", was popularized in the early 1990's. (Liker 2004.)

3.3.1 Philosophy

During their studies, Womack and Jones (2003, p. 10) have identified five core principles that form the base of lean manufacturing. These are value, value stream, flow, pull, and perfection.

The most important aspect of value is that it's always defined from the customer's point of view. This means that adding new features to the product or producing it in a new, more efficient way is only worthwhile if it is something the customer actually wants. (Womack & Jones 2003, p. 16-18.)

Value stream is the set of all activities needed to bring a product through three critical management tasks. These are the problem-solving task of getting from the product concept through design into the beginning of manufacturing, the information management task for all data needed from the order to delivery, and the physical transformation task needed to transform raw materials into finished products. The activities within these tasks can be sorted into three groups: activities that bring value to the customer, activities that do not create value but are unavoidable and activities that do not create value and are avoidable. Identifying the entire value stream usually uncovers a lot of non-value-adding activities. (Womack & Jones 2003, p. 19-20.)

The flow principle means having the product flow through the manufacturing process without having to wait. It can be seen as the opposite of the traditional method of batching the orders and having them wait between the phases. The batching approach is so popular because it seems intuitively more efficient and keeps all the machines and employees busy. However, lean projects have shown that the flow model of finishing one job before starting the next shortens the time from order to delivery. In addition, it is more efficient than working on big batches, even though this might seem counterintuitive. This will be addressed in more detail in section 3.3.4. Getting products to flow requires forgetting department lines and focusing on the process from the view of the product. The goal is having a single piece flow through the production process with no buffers between the different phases. (Womack & Jones 2003, p. 21-22, 52, 60.)

In order to have an uninterrupted flow, all resources must be available and all the parts to be worked on must be right. This requires that defective parts are not sent further down the line. To this end, mistake-proofing, commonly called by the Japanese term poka-yoke, is used. This means ensuring that defects are noticed before sending the part ahead. It can be implemented e.g. with visual controls. (Womack & Jones 2003, p. 60-61.)

The pull principle means letting the customer "pull" the product out of the process, meaning that nothing is produced that hasn't been ordered by a customer. This is possible because of the throughput time reduction achieved with the flow production. Implementing the pull principle makes demand estimates unnecessary. The pull principle and short throughput times ensure that the company can always sell to the customer in a reasonable time without having excess stock that will eventually end up unsold. (Womack & Jones 2003, p. 24-25.)

These four principles, namely value, value stream, flow and pull, should lead the company to a virtuous cycle of finding more and more improvement opportunities. This makes perfection a reasonable goal to aim for. The target to compete against should be perfection rather than the existing competition. (Womack & Jones 2003, p. 25, 49.)

A key element of lean manufacturing is eliminating everything that adds cost without adding value. Such activities or processes are called wastes (muda in Japanese). Wastes are found by viewing the process from the customer's point of view and determining which steps add value and which do not. Waste is reduced by eliminating the non-value-adding steps if possible and if not, minimizing the time and resource spent on them. (Liker 2004.) Different kinds of waste are studied in more detail in section 3.3.3.

Just in time (JIT), an approach invented at Toyota, is a method for attaining flow production. The idea is shipping goods in the right amount at the right time. This is achieved by producing small amounts with short throughput times. The idea is that a small amount of goods moves smoothly through the production, arriving in each destination right when it is needed. This requires changeover times to be very short. Upstream production producing only small amounts of each product and then switching over to the next one mustn't result in long waiting times or other problems. Downstream flow has to be smooth as well if bottlenecks and the resulting safety buffers are to be avoided. Therefore, only applying JIT to purchasing while the downstream flow, the company's own production, remains erratic will not bring as much benefit as when the whole chain works with the JIT approach. Instead, the company will need to store the parts that will not be needed yet after all. (Womack & Jones 2003, p. 58-59.)

JIT production aims to identify and consequently reduce wastes, for example by eliminating excess inventories, unnecessary material movements, scrap losses and rework. Companies that respond to fluctuations with buffers rather than the JIT principle are less efficient not only because of the wastefulness, but also because having big buffers allows the process to run suboptimally, making continuous improvement unnecessary from the point of view of the process. (Inman et al. 2011; Liker 2004.)

The 5Ss is a method for removing all unnecessary items from the workplace and having all tools clearly marked and visible. The name comes from five Japanese terms that describe practices needed for keeping the work area clean and manageable. These are seiri (organization), seiton (tidiness), seiso (purity), seiketsu (cleanliness) and shitsuke (discipline). Seiri means identifying and removing unneeded materials. Seiton means arranging materials and tools so that they are easy to use. Seiso means cleaning up the work area. Seiketsu is conducting the previous three regularly, preferably daily. Shitsuke is making a habit of following the other four. (Womack & Jones 2003, p. 61, 348, 361.)

3.3.2 Implementing lean principles in small series production

The lean manufacturing approach is aimed at mass production (Liker 2004), and fully applying lean manufacturing requires first-rate quality and consistency as well as low variation in mix and volume (McKay & Wiers 2004, p. 17). It is generally regarded that lean manufacturing is best suited for companies operating in stable conditions with standard products and predictable demand (Inman et al. 2011). Full-scale lean manufacturing is thus not well suited for small series production. Still, the philosophies behind it could be of a lot of value. For example, Stevenson et al. (2005) suggest that waste reduction could be applied in ETO companies. In fact, Sharp et al. (1999) argue that using some lean manufacturing methods is required for thriving in unpredictably changing environments.

Järvenpää et al. (2016) suggest conducting a value stream analysis as a method for systematic lead time reduction. It is a tool for visualizing the value stream of a product with the aim of analyzing the flow of materials and information and identifying all forms of waste (Stern 2015, p. 43, 66). It lists every activity that is needed for the product to move from design and customer order into a final product. The activities are then sorted into value-adding ones, non-value-adding and unavoidable and finally non-value-adding and avoidable ones. Value is defined from the customer's point of view. (Womack & Jones 2003, p. 37-44.) Times spent in the various phases are also recorded (Izumi 2015). In most cases, value stream analysis will uncover a lot of waste in the different phases of the process, bringing about a huge potential for saving time and money. The idea behind value stream mapping is to optimize the whole process of producing the product, rather than the individual steps along the way. Value stream mapping requires a high level of transparency within the different phases of the process. Ideally, this analysis should include all the actors in the supply chain (Womack & Jones 2003, p. 19-21, 37-44.) Some waste can readily be eliminated by simply flow-charting the process and identifying the non-value-adding activities from that. However, non-value-adding activities should not be eliminated too hastily, as they might be valuable for an internal customer, and so eliminating them would cause trouble elsewhere. (Koskela 2000, p. 58.)

One approach for implementing lean principles in non-mass-production environments is based on decoupling the process into two parts, a lean part in the early stages of the process and a non-lean part in the later stages. (Inman et al. 2011.) The decoupling point is the point in the process where standard parts (produced with forecasting planning) and customer specific parts (pulled by the customer) meet. The benefit of this approach is that it reduces variation in the part before the decoupling point, where parts are not customer specific. This makes production planning and control easier. The approach is generally used with very complex products that are realized as projects. (Gosling & Naim 2009.)

Because of variability, resource conflicts and queues, the very low levels of inventory that implementing JIT is supposed to bring are not attainable in job shops (McKay & Wiers 2004, p. 34). In general, the JIT approach has not been easy to implement in job shops, and its requirement for advance planning makes it unsuited for the unpredictable conditions that most companies with small series production face (Stevenson et al. 2005).

Based on their observations from organizations implementing lean thinking, Womack and Jones (2003, p. 27), claim that changing from batch to flow production could double labor productivity while producing less defects and reducing inventories and throughput times by as much as 90 percent. Implementing flow production requires knowing the takt time. Takt time is the available production time divided by the rate of customer demand. It defines how often one product must be completed on average to meet customer demand. This obviously requires knowing the level of demand quite precisely. (Liker 2004; Womack & Jones 2003, p. 55-56, 352). Unfortunately, companies with small series production rarely have the luxury of steady demand or unchanging throughput times.

3.3.3 Wastes

When it comes to implementing lean, a lot of importance is placed on waste reduction. Wastes are activities that add cost without adding value to the product. Different types of waste are typically divided into the following seven categories: overproduction, unnecessary inventory, transport, process, activity resulting from rejected product, waiting and unnecessary motion. (Carreira 2005, p. 53; Liker 2004.) The following list is based on Carreira (2005, p. 53-65).

- Overproduction means producing parts without having a hard order on them.
- Unnecessary inventory means goods that are lying idle without being worked on. For example, buying large quantities could lead to this. Another common cause is producing parts just to keep machines running.
- The transportation of material doesn't add any value to the product from the customer's perspective and must therefore be considered waste. Transporting arriving products to a receiving area before taking them to the production area where they are actually needed is an example movement that is considered unnecessary.
- Process waste comes in many forms. One is overprocessing, where an activity is done much more carefully and thoroughly than would be necessary to have a product that is good enough. This is wasting time. Another example of process waste is adding an extra task that could be eliminated by including the activity in another task. The other task might then require more effort, but the overall process would be optimized. Setup and changeover times could also be categorized as process wastes.
- Waste resulting from rejects or rework can cause huge expenses without bringing revenue. Rejects and rework often cause extra work for many different people, also outside of manufacturing. What's important is not letting defected material go any further down the line, as it would cause waste there.
- Waiting is clearly time wasted, be it waiting for parts, a tool or for a machine to finish. During this time, no progress is taking place even though expenses are running.
- Unnecessary motion refers to the movements of people. It includes movement between workstations inside of production, to where tools are located etc.

These wastes are called by the Japanese term muda. However, there are two other types of waste that are just as important to consider. These are called muri and mura. Muri is the waste of overburden, which means pushing a resource, whether a worker or a machine, beyond its natural limits. This causes quality problems and safety concerns. Mura is the waste of unevenness. It results from an irregular production schedule or fluctuating production volumes. The fluctuation can be caused by defects, missing parts, machine downtime etc. The unevenness means that there must be resources available for the highest level of production, even though less is required on average. The muda type of waste, non-value-adding activities, are the result of mura. (Liker 2004.)

Companies often start their lean implementation by eliminating muda. However, focusing solely on reducing muda without considering the other types of waste can even be harmful. (Liker 2004.) The system must remain robust towards disturbances and changes. This means that non-value-adding but necessary activities are essentially treated the same as value-adding activities, and stock and capacity levels will be higher than in fully lean systems. (Naylor et al. 1999.) Keeping an inventory might seem to contradict the lean philosophy, but accepting the waste of keeping an inventory can reduce much more waste by supporting evenness in production. Reducing inventory in a strongly fluctuating production system will lead to very erratic production, with materials running out and regular overburdening of resources. Leveling the production schedule so that over- and underutilization of resources is minimized is the preferred approach, because eliminating mura, the waste of unevenness, is essential to eliminating the other types, muri and muda. (Liker 2004.)

3.3.4 Flow

The flow principle is closely related to the concept of waste, as it is founded on reducing non-value-adding activities. They stem from the structure of the production system, from the way production is controlled and from the nature of production. Structure-related non-value-adding activities occur in a hierarchical organization, as various subtasks are done between operations. Production planning and control principles might be such that they generate waste, or the principles might be good but deviating from them can cause waste. The waste that comes from the very nature of production relates to variation and surprising occurrences, such as defects. (Koskela 2000, p. 55-57.)

Leveling the production schedule, a.k.a. eliminating mura, means having a steady flow of products rather than first rushing and then slowing down. This could require front-loading or postponing deliveries. As customer orders usually come in unpredictably, this means that the customer will not get their products exactly when they want them. The benefits are still considered more significant, because leveling production makes it more organized and ensures that resources aren't under- or overutilized. (Liker 2004.)

Improvement measures in manufacturing have traditionally been based on the transformation paradigm, which means optimizing the individual operations that turn inputs into outputs. This approach doesn't consider non-transformational activities between operations. Because of this, the possible deterioration of non-transformational activities is not noticed, and intended improvement measures might even be harmful when considering the production flow. (Koskela 2000, p. 53-54.)

Modig and Åhlström (2013) introduce the idea of resource and flow efficiency. Resource efficiency is the percentage of time a resource is used for adding value. So, in a resource efficient process there is always work for the resource. Flow efficiency, on the other hand, is the sum of value-adding time in relation to throughput time. Flow efficiency requires always having a resource available for the flow unit being processed. The flow unit can be material, information or people. The difference between the approaches is whether the flow unit adapts to the resource or the resource to the flow unit. In addition to improving flow efficiency, customer value can also be increased by increasing the speed of the process, a.k.a. shortening the throughput time. (Modig & Åhlström 2013, p. 20-28.)

Many organizations concentrate on resource efficiency rather than flow efficiency. A major problem in this approach is that it tends to lead to sub-optimization. This means that individual resources are efficient, but secondary activities are required to keep them that way. For example, having many flow units in the process generates the secondary need of prioritizing tasks. It also means higher inventory and WIP levels. This makes it difficult to have an overview of the situation and can lead e.g. to the need of looking for materials. The secondary needs can generate even more secondary needs. (Modig & Åhlström 2013, p. 48-58.)

Having no overview of the process makes fulfilling the secondary needs feel like value-adding work even though it is not. The secondary needs would not exist in the first place if the primary needs, a.k.a. the main tasks of the process, were fulfilled sooner. High resource efficiency means maximizing the amount of time that resources are used for value-adding work, which fulfilling the secondary tasks isn't. This is called the efficiency paradox: the resources are constantly busy, but value is not added effectively. The key to solving the efficiency paradox is removing the need for the secondary activities. This means making the process more flow efficient. (Modig & Åhlström 2013, p. 48-65.) In the words of Modig and Åhlström (2015, p. 65), "*not* focusing on utilizing resources makes it possible to free up resources."

It is very difficult to combine resource and flow efficiency. The goal in a resource efficient process is to always have work for a resource. In such a process, a well-maintained resource will thus have no available capacity. Because of variation, there must then be a buffer of flow units queuing for it. This in turn increases throughput time, decreasing flow efficiency. The phenomenon is demonstrated by Little's law. It states that throughput time is the product of the amount of flow units in the process and cycle time. Short throughput times are important for flow efficiency, whereas a large amount of flow units in the process is important for resource efficiency. (Modig & Åhlström 2013, p. 34-36, 44-47.)

Little's law also implies that the decisive stage of the process is the one with the longest cycle time, a.k.a. the bottleneck. It dictates the throughput of the entire process. The law of bottlenecks states that throughput times are longer when bottlenecks are present. Bottlenecks appear when tasks have to be completed in a certain order, as is usually the case in production, and when variation is present. (Modig & Åhlström 2013, p. 34-44.)

Combining high flow efficiency with high resource efficiency is made even harder by variation. Variation can be caused by resources, flow units or external factors. Regardless of the type of variation, it affects either the arrival time of flow units into the process or the processing time. (Modig & Åhlström 2013, p. 40-41.) The relationship between variation, throughput time and resource utilization is shown in figure 4. It illustrates the so-called Kingman's formula, an equation that describes queuing phenomena (Elias 2016).

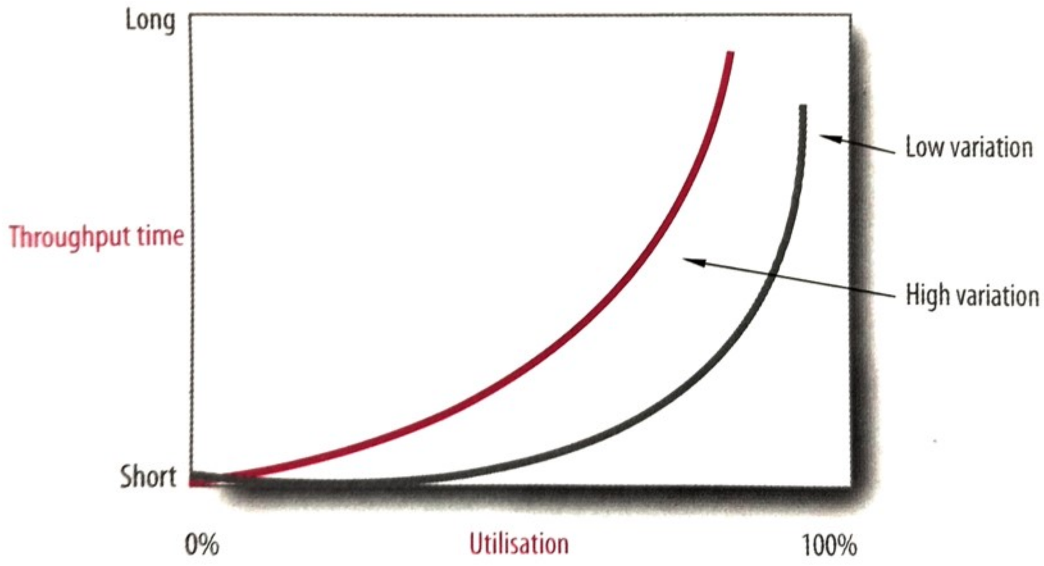

Figure 4. *The relationship between throughput time, resource utilization and variation (Modig & Åhlström 2013, p. 42).*

It can be seen from figure 4 that the relationship between resource utilization and throughput time is exponential. Thus, the closer resource utilization is to 100%, the bigger the impact on throughput time. Another notable aspect is that the more variation there is, whether arrival or process variation, the longer the throughput times are at a given level of resource utilization. If there were no variation, queues would not be formed. These points describe the law of the effect of variation. (Modig & Åhlström 2013, p. 43-44.)

The three laws, Little's law, the law of bottlenecks and the law of the effect of variation, are mathematically proven and universal. So, ways to improve flow efficiency must be derived from them. Eliminating causes of queues will reduce the amount of flow units in the process. Working faster or adding resources will reduce cycle time. Eliminating, reducing or managing variation in the process will decrease throughput times at a given level of utilization. (Modig & Åhlström 2013, p. 31, 45.)

Whether a company wants to focus on resource efficiency or flow efficiency is a strategic decision. There are no absolutely better or worse options; the goodness of the decision depends on the organization's situation. Excellent flow efficiency means always having capacity available for processing a flow unit. This provides better customer service but is more expensive. (Modig & Åhlström 2013, p. 108-115.)

3.4 Agile manufacturing

Uncertainty is an integral part of today's business world (Zhang & Sharifi 2000). Agility is a way of doing business that aims for successful operation in this environment. The constant and unexpected change calls for quick and effective reactions. (Gunasekaran 1999.) Agile manufacturing requires flexibility, but must also consider other aspects. Agile companies must simultaneously strive for such objectives as cost, quality, dependability and state-of-the-art products. (Yusuf & Adeleye 2002.) The main driver of agility is change (Yusuf et al. 1999). Wiendahl et al. (2007) define agility as the changeability of an entire company.

The concept of agile manufacturing was first introduced in the early 1990's, and has since been considered an important model for companies to remain competitive (Harraf et al. 2015; Vázquez-Bustelo et al. 2007; Sharifi & Zhang 2001). It aims at responding to change effectively and quickly while taking advantage of the volatile market situation (Zhang & Sharifi 2000). Agile manufacturing combines aspects of earlier methodologies, such as lean manufacturing, total quality management, mass customization and flexible manufacturing systems. It is still clearly distinct from these, especially when it comes to the emphases placed on different capabilities. Lean manufacturing, for example, favors efficiency over other values, while the main focus of agile manufacturing is on responsiveness. (Vázquez-Bustelo et al. 2007.) It has been suggested that agile manufacturing is a better fit for ETO organizations than lean manufacturing. However, it has also been stated that lean is a prerequisite for agility. (Gosling & Naim 2009.) For example, Sharp et al. (1999) state that agile manufacturing is based on the foundation of lean manufacturing, and that companies striving for agility should implement lean methods. Yusuf & Adeleye (2002) argue that lean is necessary for sustainably operating in the turbulent market, but not enough by itself. This is because it requires foreseeable and perfectly reliable resources and focuses too much on standard products. Agility answers to these limitations.

Gunasekaran (1999) sorts the qualities of agile manufacturing into four key concepts, which are strategies, technology, people and systems. Below, the categorization is used to introduce characteristics that support agility.

3.4.1 Strategies

Agile companies are able to quickly reconfigure their business in order to react to changes or new market opportunities (Yusuf et al. 1999). They usually have flat hierarchies, no strong boundaries and are process focused and team based. They strive for continuous improvement and are constantly evaluating their processes in order to be able to operate optimally. (Harraf et al. 2015.) They should implement a quality culture, where workers know what is considered acceptable quality and report deviations when they notice them (Järvenpää et al. 2016).

Strategic alliances and tight cooperation in the supply chain support agility. Cost and responsiveness but also quality, IT skills and flexibility should be considered when selecting partners. (Gunasekaran 1999.) By cooperating, companies can achieve levels of responsiveness that would be unattainable for them individually. Virtual enterprise is referred to as “the climax of cooperative venturing”. Forming a virtual enterprise means that companies cooperate on corporate and operational levels. Agile teams work across company lines, and resources and skills are spread to better and quicker respond to customer needs. (Yusuf et al. 1999.) Cooperation and integration of operations should also be encouraged inside the company (Vázquez-Bustelo et al. 2007).

Modularity improves agility by allowing the company to respond to customer requirements quicker. Delaying the detailed specification of products can also better accommodate last-minute changes. (Yusuf et al. 1999; Gehani 1995.)

Concurrent engineering means that different parts in the company, including engineering and manufacturing, work simultaneously to seize opportunities and solve problems. It is an important enabler of agile manufacturing, as it emphasizes quick responses. Rapid prototyping supports this. (Sharp et al. 1999.)

3.4.2 Technology

According to Yusuf et al. (1999), a company must have changeability on physical and logical levels. Physical changeability means having adaptability in the physical production systems (Yusuf et al. 1999). Hardware has to be flexible and support short changeover times (Gunasekaran 1999). Logical changeability refers to using reconfigurable process planning and adaptive production planning and control to efficiently respond to changes (Yusuf et al. 1999). To this end, advanced information technology is of great importance to agile manufacturing (Koskela 2000, p. 67).

Jin-Hai et al. (2003) consider IT an essential condition for implementing agile manufacturing. Rapid and reliable information systems are needed to enable an information flow between workers and across departmental lines. This is especially important in larger companies. (Sharp et al. 1999.)

Tu (1997) argues that traditional scheduling tools are unsuited for agile manufacturing with one-of-a-kind products, because they can’t properly adjust to the ever-present uncertainties. Production schedules for one-of-a-kind products tend to be just generic guidelines or even useless in the worst case. A more adaptive scheduling system with feedback loops is needed to react to changes in real time. (Tu 1997.) MES and APS systems enable fast and easy rescheduling and accurate detailed scheduling, and are thus important enablers of agile manufacturing (Järvenpää et al. 2016). Having no MES means that collecting data, particularly history data, is a more arduous task. In addition, the workers on the factory floor don’t have the whole picture of the process, which hinders their ability to make good decisions. Using paper documents causes similar issues, such as hampered information flow and transparency. Data could also be unreliable, e.g. because of unsystematic time stamping. This means that there is no reliable history data for production planning and control to use. (Järvenpää et al. 2016.)

3.4.3 Systems

Flexibility means the ability of the production system to quickly and conveniently change from one type of product or component to another. This is done by changing manufacturing processes, material flows and logistical functions. (Wiendahl et al. 2007.) Flexible manufacturing systems are built so that they can quickly and cost-effectively produce different kinds of products in varying capacity within pre-defined limits. (ElMaraghy 2006). It is impossible for ETO companies to know the precise product mix much beforehand. High flexibility is required to deal with the resulting variation, both in the volume and mix of products. (Gosling & Naim 2009; Jahnukainen et al. 1997, p. 16.)

Flexibility can be divided into product, operation and capacity flexibility. Product flexibility is the ability produce a variety of parts on the same equipment. Operation flexibility refers to manufacturing different sets of products using several different resources and processes. Capacity flexibility is the ability to adjust to different levels of demand. These capabilities must be included not only on technical but also on organizational level. (Wiendahl et al. 2007.)

Capacity flexibility can be achieved by reserving excess capacity in the process in case of spikes in demand. Temporary spikes can also be accounted for by overtime, although this solution only works for a short time. If demand spikes are common, buffers are often required. Many companies also have parts that can be produced in another company if demand is higher than available capacity. (Jahnukainen et al. 1997, p. 16.)

Reconfigurability is an engineering technology for rapidly responding to market and product changes. In contrast to flexible systems, where changeability is achieved through built-in functionalities, reconfigurable systems are designed to be able to rapidly change their structure. The objective is providing the right functionality and capacity exactly when needed. Reconfigurable manufacturing systems are designed for manufacturing a family of parts. There are three characteristics that are crucial for reconfigurability. These are customization (flexibility limited to a product family), convertibility (ability to change functionality of machines or systems) and scalability (ability to easily modify production capacity). (Koren & Shpitalni 2010; ElMaraghy 2006.)

Having appropriate information and support systems in place enables quick reactions to changes and is needed for the flexible and dynamic cooperation between the actors in the company and across the supply chain. Information systems support other agility enablers, such as the virtual enterprise. (Gunasekaran 1999.) Integrating the various computer systems that are used in production leads to better results (Yusuf et al. 1999; Gehani 1995), but realizing the integration is one of biggest challenges of agile manufacturing (Gunasekaran 1999). This claim is supported by Järvenpää et al. (2016). They identified the lack of proper IT tools for production and monitoring as one of the most critical challenges hindering agility in Finnish manufacturing companies, along with using paper documents in data collection. The lack of IT tools meant not having APS or MES systems.

3.4.4 People

Agile companies need to develop teams of highly-trained, motivated and empowered people (Wiendahl et al. 2015, p. 79; Vázquez-Bustelo et al. 2007). It is even seen as “the ultimate factor for success” (Wiendahl et al. 2015, p. 80). An important feature is working in cross-functional teams, where people are able to rapidly switch to other tasks or even change job descriptions to fit the demands of the situation (Sharp et al. 1999; Gehani 1995). Agile companies see their workforce as an asset rather than a cost to be minimized. Their continuous training and education is considered an investment. People are encouraged to be creative and think wider than just about the task they are required to do. (Sharp et al. 1999.) Forming a strategy for worker skill development is a good way of improving agility in a manufacturing company (Järvenpää et al. 2016). Often the skills are listed in a competence matrix. To really tap their potential, the matrices should be used in production planning and control. (Järvenpää et al. 2015.)

Having several approval steps before the front-line employee is a major source of delays in companies. Empowering employees to quickly respond to arising concerns by making good decisions and taking remedial action would therefore speed up order fulfilling, improving agility. (Yusuf et al. 1999; Gehani 1995.) Employee supervision should be kept to a minimum. “Macro-management” is encouraged. This means coaching and supporting, providing challenging goals and the resources needed to meet them. Management lets employees decide what means they use to meet the goals. This is notably different from the traditional approach of centralized decision making. (Sharp et al. 1999.) Empowerment also helps boost worker morale (Harraf et al. 2015). Harraf et al. (2015) argue that because of the increased responsiveness, decentralization is preferable to centralization from the point of view of overall agility. However, they note that centralized decision making tends to be quicker in the case of a crisis.

Seamless information flow is an essential requirement for agility. Communication, both inside the company and to external parties, is required to be able to effectively react to change. Especially bottom-up and horizontal communication are important for organizational agility. (Harraf et al. 2015.) Work in agile organizations is collaborative rather than solitary. Information flows are defined by project structures rather than organizational structures, and direct communication is emphasized. Appropriate information technology plays an important role in enabling the continuous flow of information. (Forsythe 1997.) Buy-in of the workforce is required for the successful implementation of agility (Gunasekaran 1999), and bottom-up communication decreases resistance to change and increases potential for better solutions to arising problems. Horizontal, interdepartmental communication minimizes the amount of overlapping and repeated activities. (Harraf et al. 2015.)

4. THE RESEARCH PROCESS

This chapter describes the questions and boundaries guiding the research as well as the strategy and methodology that were used to carry it out.

4.1 Research questions and boundaries

The motivation for this study arose while working on a project aimed at improving delivery reliability in a company with small series production. Statistical analysis was used to examine the situation. Data of past due date postponements was categorized based on root cause, but this was not a simple task. As a hypothetical example, if an order had to be postponed because rework took a long time, was the root cause the defect that caused rework to be needed, or not having enough capacity to carry out the rework? Or was it the worker's lack of training which caused the defect, or the rushed orders that caused the lack of capacity? Or was it perhaps the constant need of reworking parts, which led to rushed orders and stress, creating more defects? One goal of the project was pinpointing the areas with the highest potential for improvement and suggesting improvement measures, but how could it be done when even defining the root causes was challenging? The initial approach taken proved to be too inflexible and insufficient for analyzing the complex situation. Another approach was needed to make sense of the situation.

The goal of this study was introducing a better method for analyzing the current state. Therefore, the main research question was

- How to plan and execute a current state analysis in a delivery reliability improvement project?

To be able to model the situation in a way that reliably represents all relevant aspects of the situation, including the ones that aren't obvious, a good understanding of the process and the influences behind it was needed. This required diverse information, a lot of which was the kind that wouldn't be found in company documents or other readily available data sources. Still, it was needed to be able to reliably analyze the situation. Therefore, a supporting research question to be considered was

- How to gather the relevant data for the analysis?

The initial approach for visualizing the situation in the case project was sorting causes of postponements into categories based on their perceived root cause and representing their frequency with bar graphs. This did not give any implication of the complexity behind the cases or consider the interrelationships between the categories. To overcome this obstacle, the next research question for this study was

- How to model the current state of a complex situation?

The model needed to be elaborate enough to represent the situation without oversimplification, yet simple enough to be intelligible and useful.

Another problem with the initial analysis approach was that the process of sorting cases into categories was highly subjective. Deciding which part of the event chain or chains to choose as the root cause greatly affected the outcome of the analysis. So, it could not be guaranteed that the attained results fully corresponded to the real situation. To avoid similar issues with the new method, the following question needed to be addressed:

- How to verify the model of the current situation?

Lastly there was the end goal of the case project, namely suggesting potential improvement measures. The current state analysis had to direct attention to the areas with high potential for improvement. The last research question was then

- How to identify opportunities for improvement?

Since there was no time for carrying out improvement measures in the case company, this thesis focuses on the current state analysis and identifying opportunities for improvement. Executing the suggested action is ruled out of scope of the study. Concerning delivery reliability, this study concentrates on the timeliness aspect.

4.2 Research strategy and methodology

This research was carried out as a case study. A case study investigates one or a small amount of entities, events, individuals etc. intensively and in great detail, enabling the creation of a holistic view (Noor 2008). It is often concerned with a process (Hirsjärvi et al. 1997, p. 131) and should thus be well fitted to studying the process of executing a current state analysis. Case studies typically answer "how" and "why" questions (Yin 2009, p. 8-13; Noor 2008). Notably, all the research questions in this study begin with the word how. Case studies have been criticized for their lack of generalizability (Noor 2008). Yin (2009, p. 15) addresses this critique by stating that the generalization of the results of a case study happens by comparing its results to previously developed theory.

Case studies can be categorized based on whether the results of the study come from one or more cases. Multiple-case studies have better validity and are therefore preferable, provided that the choice to do multiple cases exists and there are enough resources available. (Yin 2009, p. 46-47, 60.) This study is a single-case study, because the choice for doing multiple cases did not exist and the resources were limited. After all, the motivation for this study came from the need of one company. Doing a single-case study also supported keeping the scope of the study reasonable.

This case study was qualitative in nature. Qualitative research studies the subject holistically and from many angles. It is fitting in complicated situations where making precise measurements is difficult. (Hirsjärvi et al. 1997, p. 157.)

This study followed the constructive research approach. It is a kind of case research with the aim of combining practical problem solving with scientific contribution. This is achieved by producing a construct and implementing it in a real-world situation. The constructs can be processes, practices, tools or organizational charts. The philosophy behind the constructive research approach is that knowledge should have instrumental value. (Lehtiranta et al. 2015). The main research question, "how to plan and execute a current state analysis", was answered by creating an improvement method for planning and executing a current state analysis. Figure 5 summarizes the elements of constructive research.

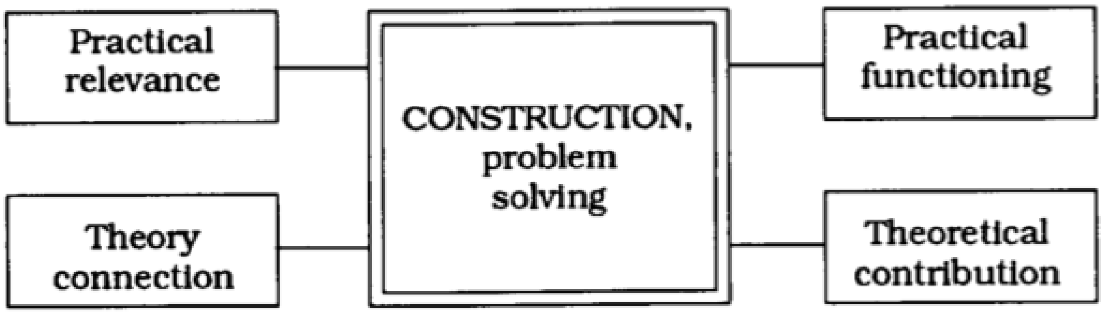

Figure 5. *Elements of constructive research (Kasanen et al. 1993).*

According to Lehtiranta et al. (2015), a constructive research process consists of six stages. These are

1. selecting a practically relevant problem
2. obtaining a comprehensive understanding of the study area
3. designing one or more applicable solutions to the problem
4. demonstrating the solution's feasibility
5. linking the results back into the theory and demonstrating their practical contribution and
6. examining the general usability of the results.

As discussed, the selected problem is carrying out a current state analysis in a complex situation. The comprehensive understanding of the study area was gained through a literature review. The topics for relevant literature were based on the four supporting research questions. Systems thinking is an approach meant for dealing with complexity. It was studied to find ways for the improvement method to address the research questions "how to model the current state of a complex situation" and "how to identify opportunities for improvement". For the model to properly portray the current state, the quiet, informal knowledge that the employees have accumulated during their work had to be included. So, to address the question "how to gather the relevant data for the analysis", literature on eliciting tacit knowledge was studied. Literature on visualizing cause-and-effect relationships was reviewed to gain ideas for answering the questions "how to model the current state of a complex situation" and "how to verify the model of the current situation".

The designed solution to the problem was a novel method for carrying out a current state analysis and identifying improvement measures to be suggested. It included building a cause and effect chart which combines insights from interviews and literature relating to delivery reliability, finding vicious cycles in the chart and aiming to break them in order to bring about improvement. Kasanen et al. (1993) suggest estimating the validity of the construct based on market tests, a.k.a. whether a manager would be willing to apply it (weak market test), adopting the construct in companies (semi-strong market test) or whether implementing the construct brings measurable benefit to companies (strong market test). However, none of these approaches were practical in this case. According to Lehtiranta et al. (2015), a pilot case study is the preferred method for validating a construct. So, the formulated improvement method's feasibility was tested by implementing it in the case company's project. In other words, a prototypical approach was taken to analyze whether the created method is fitting for effectively carrying out a current state analysis and finding ways to improve delivery reliability in small series production. How the results link back to the reviewed literature and the method's generalizability are discussed in chapter 6.

5. CURRENT STATE ANALYSIS IN THE CASE PROJECT

This chapter describes the delivery reliability improvement project in the case company. The company produces complex, customized products in small series. The project utilized an improvement method that was constructed for this study. It included identifying root causes of issues and suggesting improvement measures. Because the results from the study in the case company are confidential, all examples given in this chapter are purely hypothetical.

In order to be able to analyze the situation in the company's case, the new solution had to be able to represent the interrelationships between different actors and characteristics of the system. This was the reason that the new approach was needed in the first place. Implementing the philosophy of systems thinking, the model should help see the structure or structures that direct the behavior of the actors in the system. It must also serve the end goal of providing improvement measures. In summary, the resulting model had to

- be able to model the interrelationships present in the situation
- be able to identify the root causes of problems
- be able to direct attention to possible improvement measures

The approach taken combined knowledge gathered from people in the system and findings from a literature review on the matter that is to be improved, in this case delivery reliability. They were used as inputs for a cause and effect chart, as described by Juuti and Lehtonen (2010). The chart was used to find points of leverage in the system in order to make suggestions for improvement. This approach was inspired by the project success factor identification method used by Kopra and Juuti (2016). Using ideas from systems thinking was deemed fitting for this project, because it deals with complexities and interrelated factors. These were exactly the characteristics that were lacking in the initial approach.

At the beginning of the project, the improvement method a vague set of guidelines. The method was developed during the course of the case project in the company, as experience accumulated on what worked and what didn't. The final version of the method is presented in figure 6.

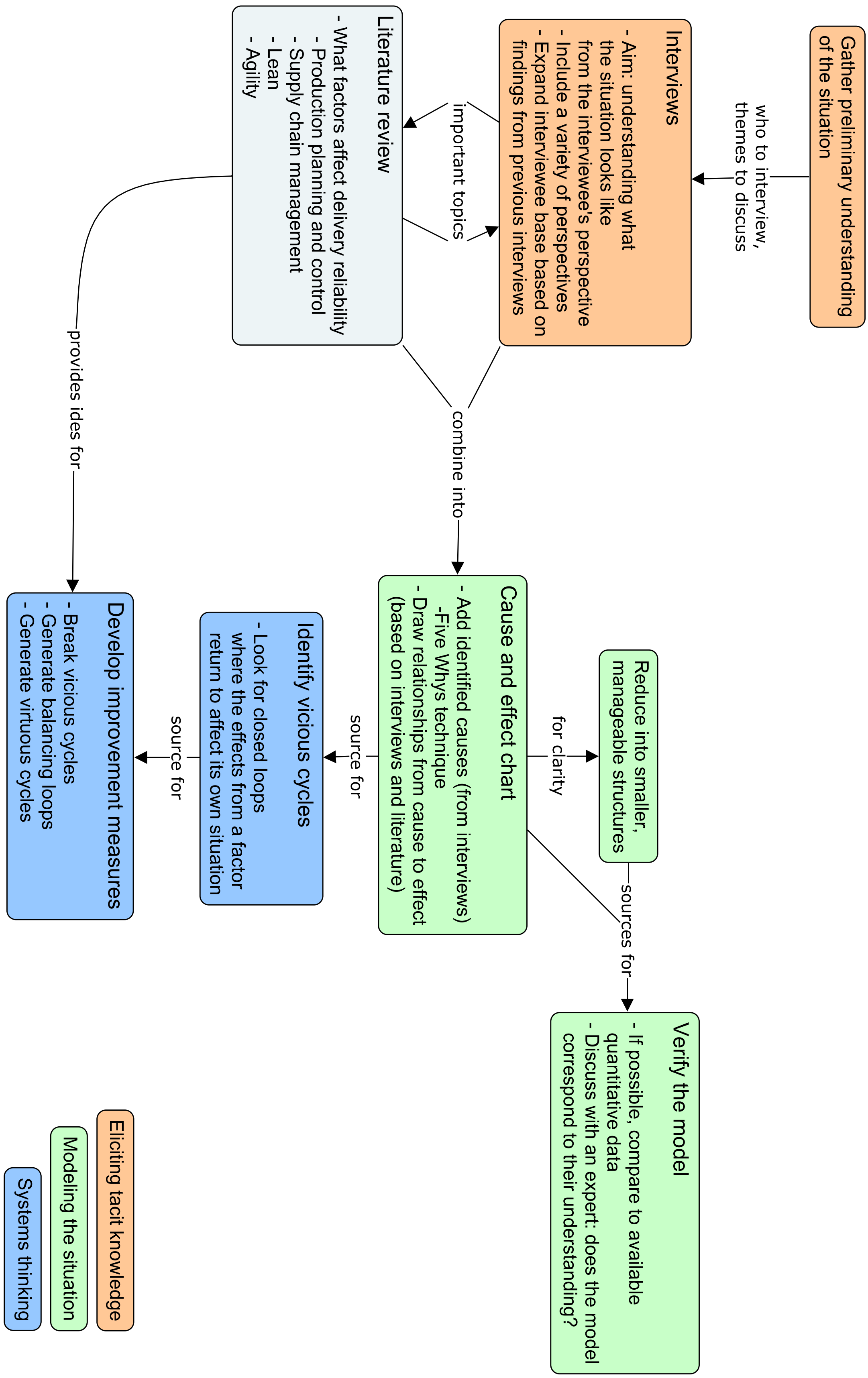

Figure 6. *The constructed improvement method.*

The process was started by gathering a preliminary understanding of the situation. The next step was conducting interviews with people from different positions in the company. The aim of these interviews was to understand what the situation looks like from the different perspectives. The preliminary understanding had given an idea of who to interview and what topics to cover. The interviewee base was widened based on findings from the previous interviews. A literature review on factors affecting delivery reliability was done around the same time with the interviews. The two complemented each other, as the literature review brought up further topics to cover in the interviews, and the interviews addressed themes that could be further studied from literature.

The knowledge from the literature review and the interviews was used to build a cause and effect chart. It included nodes with characteristics from the process and arrows between them to show causality. Smaller, more manageable structures were extracted from the chart and discussed with experts to verify that the chart gave an accurate picture of the situation. Another way used to verify the model was comparing it to available company data.

The generated cause and effect chart was analyzed by looking for vicious cycles in it. Improvement measures were suggesting so that they were able to break these vicious cycles. The previously conducted literature review provided ideas for what the measures could be.

The individual steps from the improvement method will be discussed in more detail in the remainder of this chapter.

5.1 Gathering relevant information

A preliminary idea of the company's situation was gathered from informal discussions with production planners and controllers and by studying existing company documents. The planners and controllers also provided small tours through the production areas, which gave a better awareness of the production process and offered insight into the complexities affecting the situation. The purpose was getting a cursory understanding of the basic qualities of the products and the production processes, how production planning and control was arranged and what kinds of tools it used, and of the organizational structure. This initial review of the situation also gave an idea of what things were not known or measured in the company.

Literature on topics relevant to delivery reliability was reviewed. Sources were gathered primarily through Google Scholar and the databases provided by the Tampere University of Technology library. On Google Scholar, sources that had been cited by many others were preferred. Many sources were also found from the reference lists of other sources. Findings from this literature review are presented in chapter 3.

Frequent informal interviews with production planners and controllers were conducted to understand their view of the situation. Documentation on past disturbances served as a basis for these informal interviews. They were asked why they had postponed a specific order, what had led to that situation etc., using the 5 Whys technique. Often this sparked further remarks e.g. on how things usually ran or what they felt was expected of them. This gave insight into how they saw the situation and what they considered to be the major causes for delays.

Of course, it was important to also gain other perspectives. To this end, semi-structured expert interviews were conducted. A key point was finding out how people in different positions viewed the situation and what they considered the most important issues regarding delivery reliability. The reasons why an organizational unit operates the way it does were inquired, especially if people elsewhere saw it as hindering their own processes. The attitudes people held and things they took for granted were also of interest.

The people to be interviewed were chosen with purposive sampling based on the preliminary understanding of the situation. Interviewees from the production department included department and segment managers, team leaders and shop floor controllers. In addition, people from project management, purchasing and design and development were interviewed. Most interviews were one-on-one and a few were paired interviews. The amount of time reserved for the interviews varied from half an hour to one and a half hours, with most of them lasting about one hour. When possible, the interviews were held in the interviewee's office.

The interviews were semi-structured in order to balance between keeping on topic and having flexibility for the interviewees to vocalize examples, stories or whatever they considered meaningful to the subject. Having the interviews only loosely structured made the situation more discussion-like, which is preferable for tacit knowledge elicitation. It also allowed moving to new themes that the interviewer might not have thought of.

Neve (2003) found that if an interview was started with a question that is too specific or too distant from the interviewee's own field of specialization, it was difficult to bring the discussion back to their central references. The interviews were thus started with a general question about what is done in the department. The themes for the interviews arose mostly from the preliminary understanding of the production process and from the discussions with production planners and controllers. The themes were updated slightly in order to include important topics that came up in the first interviews. Because of the confidentiality of the company data, the interview themes will not be reviewed in this thesis.

It seemed important to give the interviewees enough room to talk about a topic that they had a lot to say about. Some interviewees told of what had happened in the past even without asking them to, and as this kind of stories are very valuable when trying to elicit tacit knowledge, interrupting them would have been counterproductive. It was deemed more important to keep digging deeper into topics that stimulated a lot of conversation than getting all topics covered. So, if necessary, some questions were left out of the interview rather than interrupting or rushing the interviewee. When storytelling was not prompted without encouragement, the interviewees were asked to give examples of the topic under discussion or asked why a certain thing is done like it is. The interviewees' answers were also repeated in order to verify that the interviewer understood correctly. This is a technique recommended for tacit knowledge elicitation by Neve (2003) but was also important because the interviews were not tape recorded.

Tape recording the interviews wasn't possible for practical reasons. This meant special requirements for taking notes. Tacit knowledge is often transferred through stories, examples and metaphors, so it was most important to have these documented. This could also be done with a few key words, as in this case it was not important to capture direct quotes, but rather the ideas behind them. Still, care was taken to write down some details, such as interesting word choices. The notes were transcribed immediately, while the contexts, details and meanings of key words were still fresh in memory.

The interviews were analyzed using thematic analysis. This means looking for things that the answers had in common or where they were in disagreement. It is a well-suited approach for analyzing data from semi-structured interviews. (Saaranen-Kauppinen & Puusniekka 2006.) It was considered positive if two people in different positions had a similar understanding of some aspect. On the other hand, differing views meant that different perspectives were being included.

5.2 Modeling the situation

The situation in the company was visualized by mapping it in a cause and effect chart. It includes nodes, which represent the causes of issues, and arrows between them showing cause-and-effect relationships. Building the chart resembled the process of generating a fishbone diagram. The process was started by asking a broad question: what causes delivery date postponements? The answers were quite general, in the style of "material was missing" or "a defect occurred". Next, reasons for these general causes were added. For example, for the case of missing material the process could continue with "Why was material missing?" "Because it was delivered late." "Why was it delivered late?" "Because the supplier hadn't been monitored closely" and so on, utilizing the 5 Whys technique. One issue could have several possible causes, and these were all included in the chart. It was after the first few whys that the insights from the interviews started to become valuable. They raised issues that were not self-evident. Not knowing the answer to a 'why' question could provide a topic to bring up in a future interview.

Arrows were drawn from cause to effect. Some relationships were clear, such as late delivery from supplier leading to missing material. However, all relationships weren't so obvious, and having asked 'why' questions in the interviews was important for this part. Literature also gave insight into what kind of actions could lead to certain outcomes. Here it was important to consider the relationships between all the generated elements, so that arrows were not drawn just along the 'why' question chains, but also between them. The understanding from the literature proved useful when finding such relationships. It had helped bring context to the observations and examples described by the interviewees and suggested what could be affecting the system in the background. When drawing the arrows, it was important to carefully consider what is the cause and what is the effect with two dependent variables.

After having compiled the chart, individual cause and effect chains were followed in order to make sure that there were no contradictions to what had been learned from the interviews. Some fixes had to be made to clarify how a cause leads to an effect. This mostly meant adding nodes between related aspects where the dependency wasn't easy to understand.

Having added all the identified factors and their relationships to the model, it looked very confusing and could definitely not be interpreted by anyone else than its creator. There were too many lines crossing all around the picture to see the patterns that had evolved. So, the big picture had to be cut into smaller ones for presentational purposes. Still, it had been useful to first map out all the factors and their relationships that could be identified from the interviews. This gave an overview of all the relationships that were present. Furthermore, it was then relatively easy to remove elements in order to study a specific aspect. It also ensured that nothing was forgotten when splitting parts of the chart into more manageable pictures. Care had to be taken not to lose knowledge in the process of splitting the map into smaller pieces for studying individual aspects. The underlying idea of systems thinking is that when a system is divided into smaller parts, one tends to lose sight of the whole. So for the systemic approach to make sense, this had to be avoided.

The first attempt at building the chart was not the final version. The process was iterative, and the first couple of attempts gave ideas as to how the chart should be structured and what kind of wordings etc. were most useful in drawing out a coherent representation.

The case company's results are confidential and will therefore not be presented. However, an exemplary cause and effect chart of what the visualization of a company's situation could look like is presented in figure 7 below in order to give an idea of how to derive results from it.

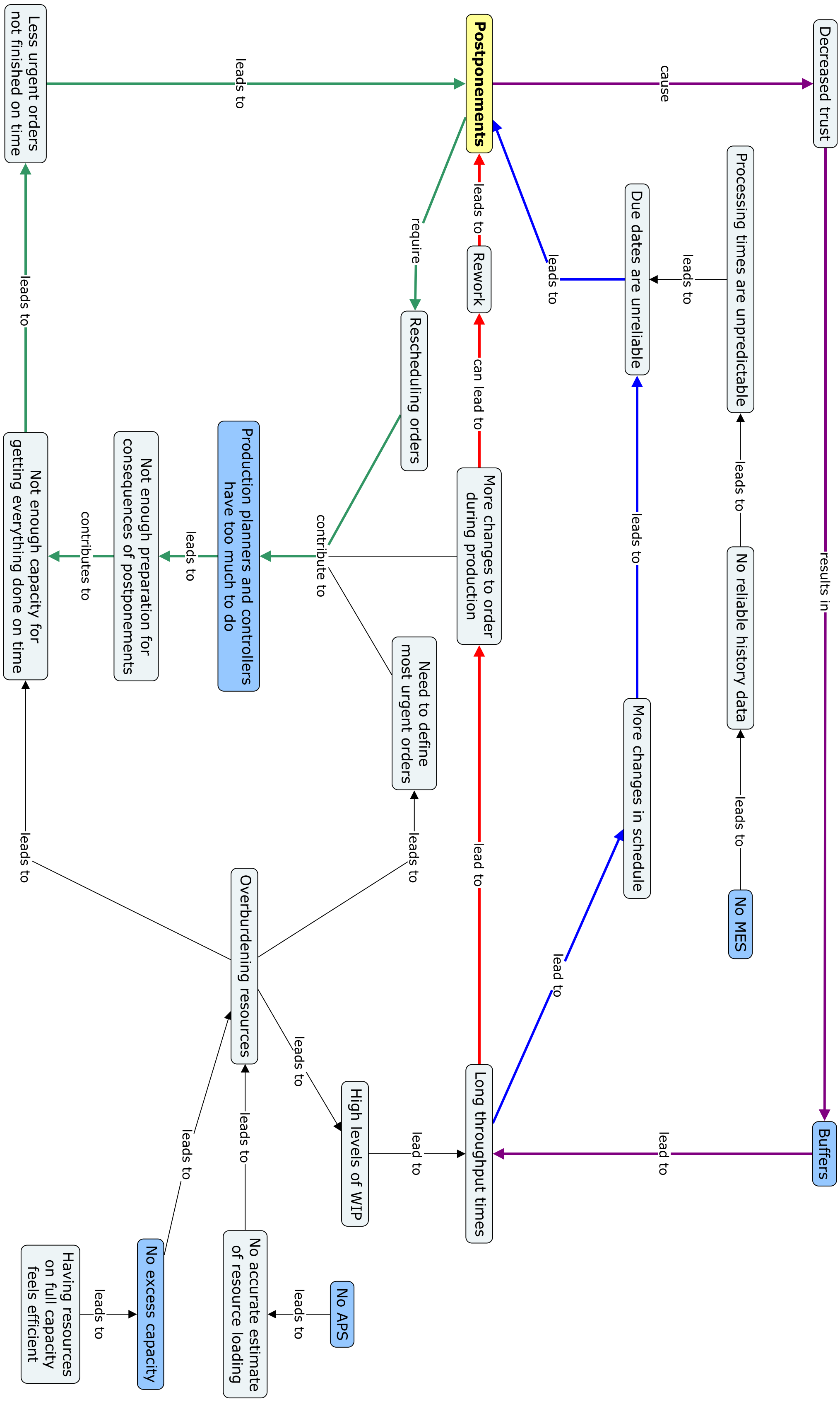

Figure 7. *An example cause and effect chart describing causes behind delivery date postponements.*

The final visualization of the situation did not include all of the identified factors or cause and effect relationships. This was to keep the picture legible. The decision on what to include in the visualization of the situation was based on the vicious cycles found in the entire cause and effect chart. Only factors that were a part of or directly affecting them were included. This was because the analysis would be based on the vicious cycles.

In order to verify the model, the final version of the chart was discussed with experts, mostly ones that had been interviewed before. The aim was to find out whether the model corresponded to their understanding of the situation. Data provided in company documents was also used to examine the plausibility of some of the discovered feedback loops. In the company's case there was quantitative data available to show correlations that fit some of the discovered causal loops.

5.3 Analyzing the model and suggesting improvement measures

According to systems thinking, the underlying causes of issues can be found in the structure of the system. Leverage to change systems can be identified by finding such structures, vicious cycles, in the situation. The cause and effect chart was thus analyzed by looking for vicious cycles in it. They were closed loops formed by the cause and effect chains.

Generally, elements that had a lot of arrows going out from them were a good place to start looking for causal loops. Elements that seemed to be a cause of many others had already drawn attention while building the chart.

The literature related to delivery reliability helped pinpoint areas that might have relevant vicious cycles in them. It directed attention to things that typically cause problems in companies and for common root causes. For example, McKay & Wiers (2004) emphasize that not accounting for future troubles will cause problems later, so looking for such structures was one approach.

The interviews were also a valuable source of ideas. Issues that were mentioned by several people proved a good starting point when looking for causal loops. However, when using such sources as a starting point, it was important to remain objective and search for structures based on the map instead of trying to fit pre-existing assumptions into the model.

In one instance, after a promising vicious cycle was found, it was noticed that the particular structure was not understood well enough; the chart didn't have enough nodes around the cycle. In this case, more interviews were arranged. These follow-up interviews were very short and to the point, emphasizing "why" and "how would you react to this kind of a situation" types of questions.

When a vicious cycle was found, literature regarding the specific topic was reviewed again to get ideas on how the situation could be changed. Recognizing systems archetypes was another way to come up with improvement suggestions.

Suggestions to improve the situation aimed to break or weaken the identified vicious cycles. Identifying root causes in the vicious cycles had indicated where improvement measures could be directed. The root causes were such that they enable or strengthen a vicious cycle. Also, they were such that they could be affected by the actions and decisions of the company.

The chart in figure 7 includes three vicious cycles. They are marked with blue, red, purple and green arrows, the purple arrows being a part of both the blue and the red cycles. The following paragraphs describe them and identify the associated root causes and possible suggestions for improvement.

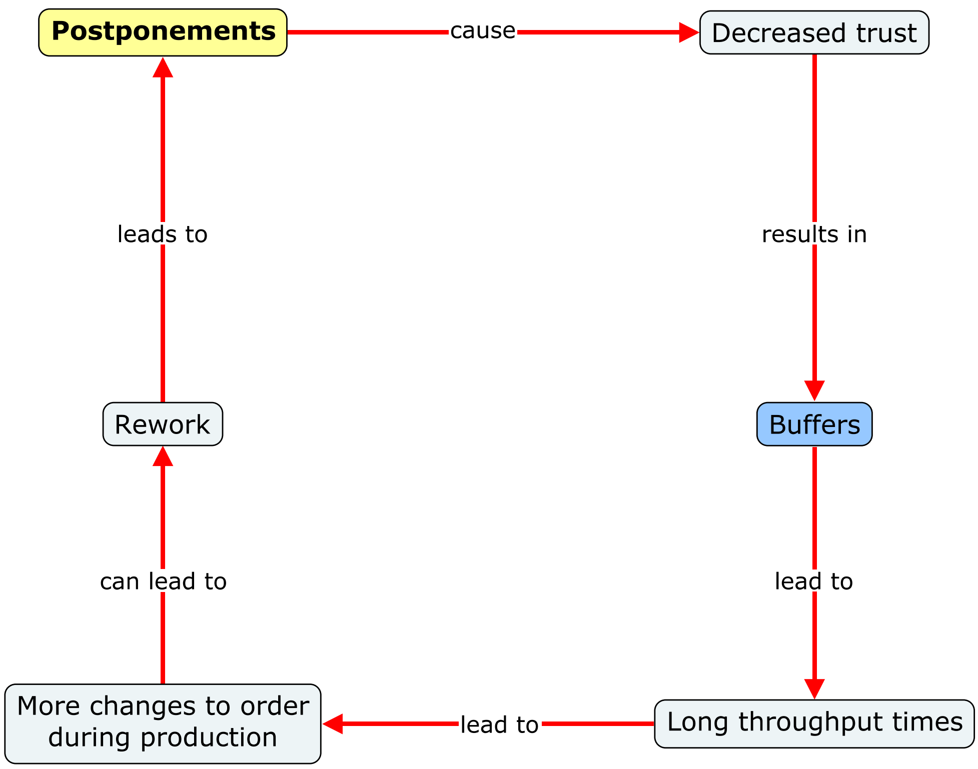

Figure 8. *Vicious cycle with many changes during production.*

The vicious cycle in figure 8 shows delivery date postponements leading to decreased trust in the ability to hold due dates, which results in adding buffers into the delivery times. This makes the production less flow efficient, meaning that throughput times get longer. When throughput times are longer, there is more time for changes to happen to the order while it is being produced. This causes delays and, at worst, having to rework already produced parts. This leads to postponing the promised delivery dates, so returning to the beginning of the cycle.

A root cause for this vicious cycle is adding buffers as a reaction to the postponements. As the loop shows, this leads to a need for even bigger buffers. Adding buffers to delivery times resembles the eroding goals structure, a systems archetype introduced in chapter 2.1.1. It is exactly the kind of short-sighted solution that non-systemic thinking tends to lead to (Senge 2006, p. 14-15). The management principle suggested by Senge (2006, p. 394), holding the original vision, can then be seen to be a good piece of advice in this case. An improvement suggestion would then be decreasing buffers to a level that would be considered sufficient if delays in the delivery times were not expected, and not increasing them even if there are delivery date postponements in the future. This would break the vicious cycle.

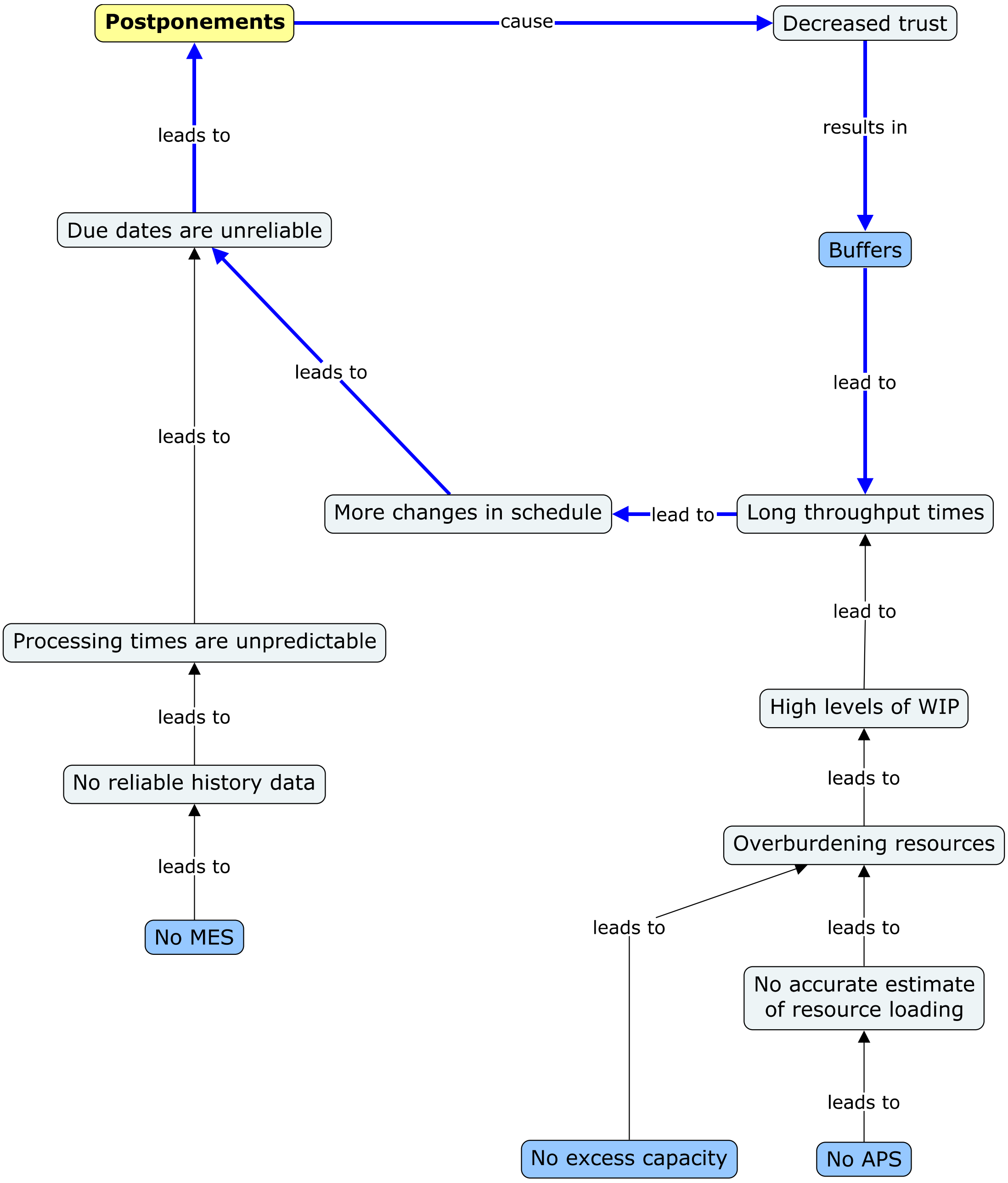

Figure 9. *Vicious cycle with unreliable due dates.*

In figure 9, postponements again lead to buffers and then to long throughput times. More schedule changes take place during the longer throughput times, making due dates unreliable and leading to more postponements.

Including buffers in the delivery times is a root cause in this vicious cycle too, but the lack of MES and APS systems strengthen it further. Not having a MES in use means that there is no precise history data available for how long processing times have been. This means that the realized processing times might be quite different to the estimates used when determining the delivery date, increasing the unreliability of the given due dates. Not having an APS system means that there is no accurate estimate of the loading situation available, leading to occasional overburdening of production resources. The overburdening is also caused in part by not having excess capacity available for spikes in demand. It leads to increased WIP levels, making throughput times even longer.

This vicious cycle includes increasing buffers, just like the vicious cycle in figure 8. Not increasing buffers would therefore be a suggestion for breaking the vicious cycle in figure 9 as well.

Other possible measures could be suggested. Implementing a MES would provide company data on realized processing times, allowing more accurate estimates to be made and thus making due dates less unreliable. A company would have a more accurate view of the loading situation of its resources if it implemented an APS system. It would alleviate the problem of overburdening resources. Implementing a MES or an APS system would then weaken the vicious cycle.

Lean literature regarding the efficiency paradox advises that concentrating on the process from the point of view of the flow unit, a.k.a. having capacity available when a product needs it, makes the whole of the process more efficient. Reserving extra capacity on the resources for surprising demand could therefore be recommended. It would ease the problem of overburdened resources, thus weakening the vicious cycle.

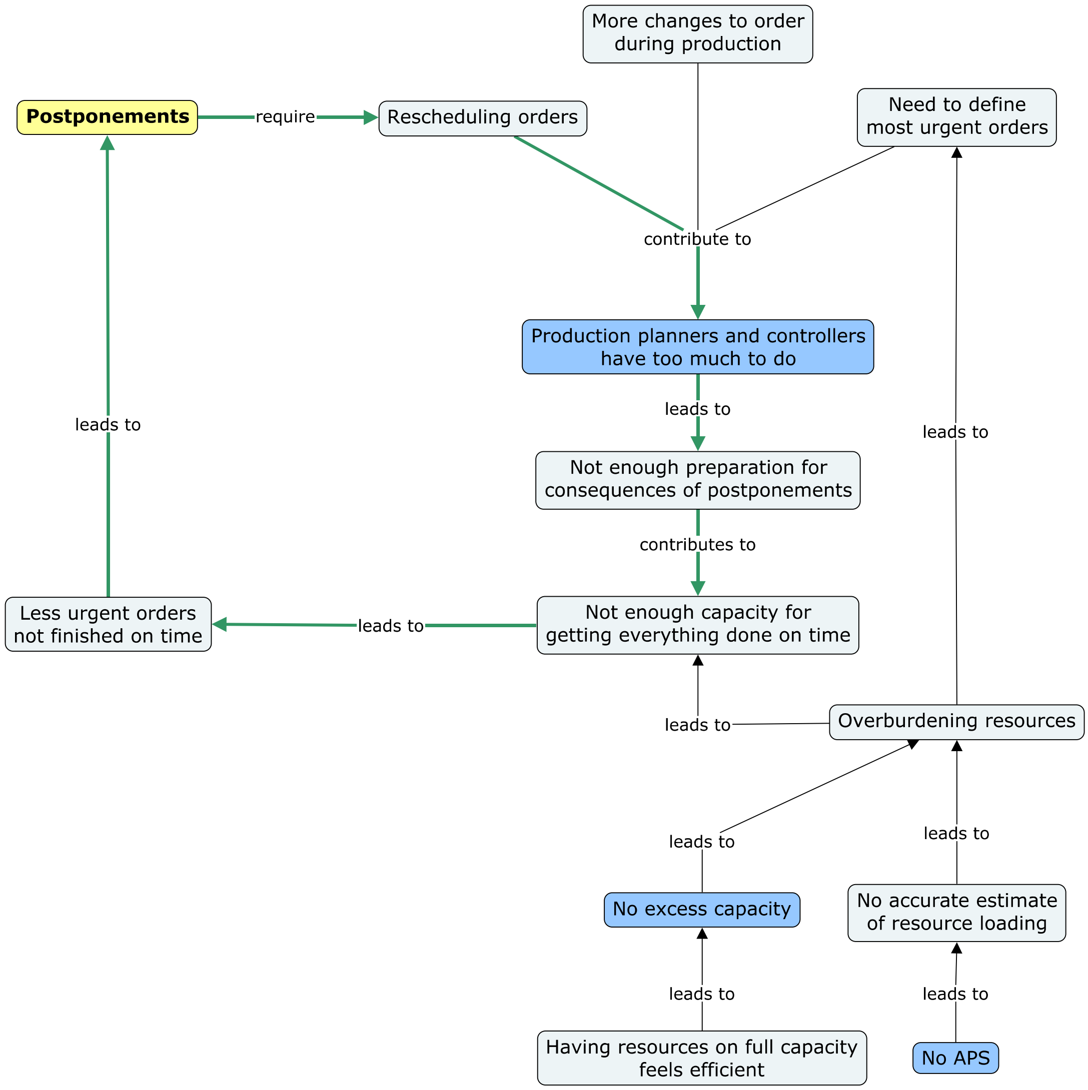

Figure 10. *Vicious cycle with overburdened resources.*

The vicious cycle in figure 10 starts from postponements causing more work for production planners and controllers in the form of having to reschedule orders. Changes during production and needing to define the most urgent orders also add to their workload. As they have too much to do, they don't have time to prepare for the consequences of the postponements. Without proper preparation, the delayed orders will disturb the production plans and cause overload at the resources. This means that there is not enough capacity to get all orders ready as planned. Some orders will then have to be postponed.

One root cause that enables this vicious cycle to keep going is the excessive workload of the production planners and controllers, which means that they don't have time to adjust plans when orders have to be postponed. Not having excess capacity or an APS system are root causes behind this vicious cycle as well, as they deteriorate the problem of lacking capacity on the production resources, thus strengthening the vicious cycle.

Literature on production planning and control recommends implementing MES and APS systems in order to make better schedules quicker. Implementing them could therefore be suggested in light of this vicious cycle. It would help with the problem of production planners and controllers having too much to do and could so break the vicious cycle.

Reserving extra capacity could be recommended for addressing this vicious cycle too. That would, together with implementing an APS system, lead to not having overburdened resources. This would mean that postponements would not lead to lacking capacity, breaking the vicious cycle.

The ideal outcome of a delivery reliability improvement project would the generation of a virtuous cycle. This means achieving self-reinforcing positive development. where having fewer delivery date postponements makes the process run smoother, leading to a further decrease in postponements.

6. DISCUSSION

In this chapter, the features of the constructed improvement method are compared to the related theory from chapter 2. The functioning of the method in the company's case is reviewed and its generalizability considered.

6.1 Comparison with theory

The major contribution of this study is introducing a novel way of carrying out a current state analysis and identifying opportunities for improvement. The method combines literature review, tacit knowledge elicitation and utilizing systems thinking. The approach is very similar to that introduced by Kopra and Juuti (2016), but is used in a different context, to improve delivery reliability.

Interviews, in particular semi-structured interviews, have been recommended for eliciting tacit knowledge (Karhu 2002; Ambrosini & Bowman 2001), and conducting them was a major part of the constructed improvement method. Question types that are recommended in literature were used in the interviews. This included asking "why" questions, asking how something is done and encouraging the interviewees to give examples. The interviews were held in the interviewee's office when possible. This is a familiar place, as is recommended by Ambrosini and Bowman (2001).

The cause and effect chart that was used to model the company's situation is based on the idea introduced by Juuti and Lehtonen (2010). It also resembles the causal mapping technique that Ambrosini and Bowman (2001) recommend for analyzing ambiguous situations and eliciting tacit knowledge. One way to verify the model was comparing it to pre-existing company data. This approach is recommended by Kollengode (2010) and Bessant for verifying the cause and effect relationships in a fishbone diagram.

Systems thinking seems to be a well-fitting approach for improving delivery reliability. The three motivations for adopting systems thinking, as stated by Reynolds and Holwell (2010, p. 15) are understanding interrelationships, dealing with different perspectives and addressing power relationships. The two former ones are clearly relevant for this study.

A system, as regarded in systems thinking, is goal driven, transforms inputs into desired outputs in a purposeful way and includes performance measures and exists in a defined environment that influences its operation (Wastell 2012). A production process clearly meets all these criteria: its goal is delivering products to customers in the right quality, amount and time, it transforms material, design information etc. into finished products and has various performance measures in place. It operates in the business environment that includes its clients, suppliers etc. that have a big influence on the process.

Often the effects of various decisions made in production planning and control are first seen after a long time. As McKay and Wiers (2004, p. 84-85) point out, the decisions often have unexpected consequences and not necessarily in the same place that the decision directly affected. The interdependencies and various perspectives within the system, the effects to and from the surrounding environment, as well as the lack of a clear solution all suggest that delivery reliability is the kind of a complex issue that systems thinking is a powerful approach for. In addition, while analyzing the challenges regarding agility in manufacturing companies, Järvenpää et al. (2016) point out that it was difficult to define which challenge was cause and which an effect. This suggests that problems affecting agility include the kind of cyclic structures described in systems thinking literature.

The constructed improvement method resembles Checkland's (1981, p. 163) seven stage methodology for improving a complex situation. Just like Checkland's methodology, the method constructed in this thesis starts with gaining a preliminary understanding of the situation, considers the viewpoints of several people in different positions and includes constructing a model using ideas from systems thinking. System dynamics was used while modeling the situation, which is one option Checkland recommends.

The method in this thesis resembles Checkland's methodology only loosely. Explicit root definitions of the relevant systems were not made and the analysis of the situation never entered as theoretical a level as in the stages 3 and 4 of Checkland's methodology. As theoretical models were not made, there could be no comparison between real and conceptual models. In general, the method constructed in this thesis includes less discussions and cooperation than Checkland's approach. In this study, cooperation with others is limited to gaining the preliminary understanding of the situation, the interviews and verifying the resulting chart with experts. This project also did not include implementing the suggested improvement measures or taking action, as Checkland words it, but that would be the next logical step. Although the constructed improvement method lacks many of the major aspects of Checkland's methodology, it can be seen that it also employs many of the same characteristics. Checkland does mention that his methodology is not intended to be used precisely, but rather as a guideline.

According to Senge (2006, p. 92-125), systems archetypes, a.k.a. structures that resemble each other, can be seen in many management situations in various fields. Identifying systems archetypes can be very beneficial, as systems thinking literature offers suggestions for improving such situations. These suggestions can then be implemented in the situation at hand. Also in this work, a structure resembling the eroding goals systems archetype could be found in the example chart in figure 7. The management principle suggested for such a case, “hold the vision”, is a sensible approach in this case. It can be seen that adding buffers to delivery times, thus allowing throughput times to get longer, just creates more need for buffering. McKay and Wiers (2004, p. 240) express a similar sentiment: when production planners and controllers have to let their goals slide, they have to make sure that it remains a one-time occurrence and doesn’t become a habit.

6.2 The feasibility and generalizability of the improvement method

The feasibility of the improvement method was demonstrated by using it to carry out a current state analysis for a delivery reliability improvement project in a case company. The approach was able to pinpoint root causes behind issues in delivery reliability and direct attention to improvement measures to address them.

Systems thinking turned out to be well-suited for analyzing the situation in the case company. As Senge (2006, p. 77) points out, the functioning of a system is hard to see when one is viewing it from within the system. The constructed cause and effect chart made the underlying structures that affect the situation visible. It thus helped see what measures could bring lasting improvement to the situation rather than just temporarily alleviating the symptoms.

The interviews proved to be a very valuable source of information, especially as sources of inputs for the cause and effect chart. The number of interviews was sufficient for getting a comprehensive understanding of the situation. The experiences from the interviews could have been further improved by having an even wider base of interviewees. Especially the views of product developers could have been interesting.

The interviews were not tape recorded for practical reasons. It could have been very useful, however, as it would have allowed checking the answers word-for-word later on if there was anything left unclear. Tacit knowledge can also be transferred in details, some of which could have been lost in this process. Tape recording would have meant less reliance on making notes of everything that was said. The focus while making notes could then have been on moods and gestures, which can also help in transferring tacit knowledge. A tape recorder would have allowed better eye-contact, also important for trust and a conversational mood. On the other hand, tape recording interviews has the possibility of making the interviewee nervous. This is especially harmful when trying to elicit tacit knowledge, because to share their stories, the interviewees must feel comfortable and trust the interviewer. Expressing unpopular opinions could feel especially difficult if being recorded. Capturing the stories, examples and metaphors was possible without a word-for-word record, and transcribing the notes immediately ensured that the meaning of short notes was not forgotten. Still, not recording the interviews was a major compromise.

Although tacit knowledge elicitation was considered during the interviews, the topic was not included in the improvement method very extensively. The knowledge acquired was not very close to the fully tacit end on the elicit to tacit spectrum; rather, it tended to be the kind that can be expressed in words by asking the right questions. One way to improve the functionality of the method would be implementing techniques designed for eliciting more ingrained tacit knowledge. This could be done for example by using drawings or the self-Q technique. Ambrosini and Bowman (2001) also suggest that causal mapping as a group exercise could be a good way for tacit knowledge elicitation. Checkland's methodology also recommends group discussions. In the company's case, arranging group discussions with the busy experts would have been very difficult, but it could have allowed adding more insight to the chart, possibly bringing to light more structures that had gone unnoticed.

Observation could have further improved the understanding of the situation. Especially systematic observation of the everyday work of the production planners and controllers as well as key production departments could have provided valuable insight. However, as pointed out by Yin (2009, p. 102), observation is a very time-consuming research method.

The analysis method of looking for vicious cycles in the process was capable method in this case. It was effective for finding root causes and locating where improvement measures could be suggested. One way to improve the analysis further could have been paying more attention to delays between the causes and effects and the impact they have on the situation.

The cause and effect chart was verified by discussing it with experts. They were for the most part the same people that had been interviewed while gathering knowledge for constructing the chart. The verification of the model could then have suffered from subjectivity.

The other way that the model was verified was by comparing it to statistically analyzed company documents. This was positive for the quality of the case study in the company because, as Yin (2009, p. 20) mentions, using multiple sources of evidence improves the validity of the study. However, performing the statistical analysis demanded a lot of work. In this case it was practical to use, as such analyses had already been done before beginning the work with the new method. Using them to verify the model didn't require much additional effort. However, if the improvement method were used in another case, it is questionable whether doing statistical analysis just for the sake of verifying the cause and effect chart would be worth the required effort. The way of verifying the model should then possibly be reconsidered. One option would be to improve on the discussions with experts. There should be enough time reserved for going through the structures in detail. The people that are asked to give their opinion on the accuracy of the cause and effect chart could also be others than the interviewees.

The new way to analyze the company's situation was well-suited for the case. It was less subjective than the initial approach and allowed including the complexities of the real situation into the analysis, unlike the previous method that was based on statistical analysis. The approach constructed in this thesis was able to direct attention to the root causes of problems and led to suggesting measures that have potential to bring long-lasting improvement to the situation.

Having multiple cases would have improved the validity of the results. Unfortunately, there was no chance for testing the construct in more than one case. The validity of the improvement method could be better assessed if it were implemented in another case. The steps in the method are generic enough that they could easily be utilized in another company. What was needed for completing the current state analysis was familiarity of the company's situation, products and processes, access to literature on the matter to be improved and the possibility to interview people from different positions. Having access to data on previous deliveries was beneficial for verifying the identified structures.

This thesis focused on delivery reliability in small series production because that is what the case company has. However, the improvement method should be well applicable in other kinds of environments as well, as there is nothing in it that is specific to small series production or even to the manufacturing industry. It could also be used in an improvement project regarding something else than delivery reliability. In that case, the literature review should address the matter to be improved.

7. CONCLUSIONS

The objective of this thesis was to develop a method for planning and executing a current state analysis and suggesting ways to improve delivery reliability in small series production. A constructive research approach was taken, with the improvement method being the construct to be generated. The method was tested by using it to analyze the situation in a company's case. It was used to identify root causes behind delivery date postponements and to suggest improvement measures. The new method was more efficient in providing results than the initially taken approach that had been based on statistical analysis.

The improvement method presents a novel way of analyzing the current state in a company and of identifying opportunities for improvement. It makes use of theoretical knowledge from literature and the employees' knowledge, including tacit knowledge that they hold, gathered from interviews. These are combined into a cause and effect chart, which shows the causal relationships between the discovered factors that affect delivery reliability. The chart is analyzed using ideas from systems thinking. In practice, this means looking for vicious cycles. The root causes of issues regarding delivery reliability are such that they enable and strengthen these vicious cycles. Sustainable improvement to the situation can therefore be attained by addressing the root causes so that the vicious cycles are broken. This guarantees that the improvement brings a lasting change to a root cause instead of temporarily alleviating a symptom.

The main research question in this study was "How to plan and execute a current state analysis in a delivery reliability improvement project?". The constructed improvement method answers this question by offering guidelines for carrying out a current state analysis.

The first supporting research question was "How to gather the relevant data for the analysis?". A part of the improvement method is gathering knowledge from literature and from interviews. The literature was about what generally affects delivery reliability. The interviews were conducted to gain a deeper understanding on what the situation looks like from different perspectives.

As the answer for the supporting research question, "How to model the current state of a complex situation", the improvement method includes building a cause and effect chart. It consists of nodes that portray matters that affect delivery reliability, and arrows between them that show the cause-and-effect relationships between them.

The next question was “How to verify the model of the current situation?”. The constructed cause and effect chart was verified by discussing it with people who are familiar with the situation to see if it corresponds with their understanding of it, and by comparing the emerged cause and effect relationships with pre-existing company data.

The last research questions was “How to identify opportunities for improvement?”. Opportunities for improvement were found by identifying vicious cycles in the system. The improvement measures were such that they are capable of breaking these vicious cycles.

Overall, the improvement method constructed in this thesis was well-suited for a delivery reliability improvement project and met the requirements set for it. The cause and effect chart allowed modeling the situation so that the interrelationships between different factors were included. It was able to identify root causes of problems and subsequently direct attention to ways of improving the situation.

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